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SPIRAL BEVEL GEAR AND PINION FORGING DEVELOPMENT PROGRAM

FINAL TECHNICAL MANAGEMENT REPORT

FEBRUARY 29, 1972

U. S. Army Aviation Systems Command
St. Louis, Missouri

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13. ABSTRACT

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After the planned process development was completed, gears were finished from the precision forgings so that the preformed teeth were finish ground using the same operations as the equivalent cut gear. Metallurgical analysis confirmed that favorable grain flow in the tooth sections was achieved and case and core properties were to specification. Limited single tooth fatique testing demonstrated that the forged teeth were at least equivalent to cut teeth.

A production quantity of forgings was made to establish die life and overall gear costs. A comparison with cut gear costs proved that the forged tooth gear is competitive with conventionally produced cut gears.

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FOREWORD

This final report compiles and summarizes the work and results of an effort conducted under a U.S. Army Contract DAAJ01-69-C-0614(IG) by the Materials Technology Laboratory of TRW Inc.

The program advancing the state-of-the-art for the manufacturing of spiral bevel gears, was directed by Mr. D. Roger Smoak, Project Engineer, U.S. Army Production Equipment Agency, Manufacturing Technology Division, Rock Island, Illinois; and Mssrs. Robert Vollmer and Ronald Evers, U.S. Army Aviation Systems Command, St. Louis, Missouri.

The development and test work for this program was performed in the period between June 1969 and December 1971. All the development work was done at the Tapco plant of TRW Inc. in Cleveland. Gear and EDM electrode finishing was done by the Power Transmission Division - Litton Industries. Engineering inputs for the gear design data and gear tooth test conditions were provided by the Vertol Division of the Boeing Aircraft Corp. The single tooth bending fatigue tests were performed at Battelle-Columbus Laboratories. These support services were provided in a truly professional manner and the cooperation received contributed to the accomplishments in the program. The interest and assistance received from the many individuals participating in the program is gratefully acknowledged. Special recognition is extended to Mr. A. Lemanski, The Boeing Company, Mr. A. Coppee, Litton Industries and Mr. H. Mindlin, Battelle Laboratories. Mr. Carl Nau of TRW contributed the important stress analysis to the die design and Mr. J. Kusner, TRW Manufacturing Supervisor was especially helpful in furnishing production facilities and capable personnel on a timely basis.

John Lazar served as Program Manager under the overall direction of Department Managers, Dr. E. A. Steigerwald and Mr. J. A. Alexander.

Submitted by: J. L. Lazar
J. L. Lazar

Approved by: John A. Alexander
J. A. Alexander

TABLE OF CONTENTS

		Page
1.0	INTRODUCTION	1
2.0	DESCRIPTION OF GEAR SET, PROCESS AND TOOLING	3
2.1	Specifications for Gear and Pinion	3
2.2	Process Design	3
2.3	Gear Forging Tool Design	15
2.4	Pinion Forging Tool Design	17
2.5	Die Material Selection	20
3.0	AUXILIARY TOOLING DESIGN, FABRICATION AND DEVELOPMENT	26
3.1	EDM Electrode Design and Fabrication	26
3.2	EDM Fixture Design	27
3.3	Forging Die Instrumentation	32
3.4	EDM Machining of the Dies	37
4.0	DEVELOPMENT PHASE	41
4.1	Gear Forging Development	41
4.1.1	Cold Coin Corrective Operation	45
4.1.2	Qualification of First Development Gear Forgings	49
4.1.3	Die Failure Analysis and Corrective Action	52
4.1.4	Gear Form Refinements to Final Configuration	59
4.2	Pinion Forging Development	71
5.0	PRODUCTION FORGING PROOF PHASE	78
6.0	FINISH MACHINING PHASE	95
7.0	MECHANICAL TESTS AND METALLURGICAL EVALUATION	107
7.1	Mechanical Tests	107
7.2	Metallurgical Evaluation	117
7.2.1	Case Depth	117
7.2.2	Metallurgical Structure	119
7.2.3	Tooth Failures	124
8.0	ECONOMIC ANALYSIS	133

TABLE OF CONTENTS (continued)

		Page
8.1	Direct Labor Operations and Material Costs	133
8.2	Direct Costs of Consumable Tooling for Precision Forging	137
8.3	Cost Summary	140
9.0	CONCLUSIONS AND RECOMMENDATIONS	142
9.1	Economic	142
9.2	Technical	142
9.3	Production Potential	142
10.0	REFERENCES	144
	APPENDIX A	1a

LIST OF ILLUSTRATIONS

Figure		Page
1	Cross section of the Ch-47 transmission nose gear box	4
2	Spiral bevel gear set assembled in bearing cartridges	5
3	Semi-finished spiral bevel gear and pinion set. Beoing-Vertol CH-47 helicopter nose box transmission	6
4	Pinion forging design	7
5	Gear forging design	8
6	Rigid frame single crank type mechanical press used for close tolerance forging of spiral bevel gears	11
7	Gear forging process layout	13
8	Billet and preform layouts	14
9	Design layout for gear preform and hot coin forging tooling .	16
10	Pinion forging tool drawing	18
11	Pinion forging process layout	19
12	Die diameter change after 500 pieces	23
13	Carbon and brass EDM electrodes	28
14	Illustration of EDM fixture set-up	30
15	Cast and EDM electrode set-up for determining the mean lead angle	33
16	Checking the gear electrode mean lead angle	34
17	Forging die load cell circuit diagram	38
18	Die temperature and forging force instrumentation	39
19	Gear forging tooling installed in press	42
20	Forged spiral bevel gears	44
21	Gear forging die temperature and force recording	46

LIST OF ILLUSTRATIONS (continued)

Figure		Page
22	Design layout for gear cold coin tooling	48
23	Semi-finished spiral bevel gear model and dimensional reference gage	50
24	Orientation of fracture in H-21 gear die. Scale-half size	54
25	Adjacent fracture surfaces, unetched hot coining die, spiral bevel gears. Scale - full size	56
26	Partial view of fractured section, hot coining die, spiral bevel gear. Scale - 2.5X	57
27	Division of forging die into triangular and quadrilateral toroidal elements for ELAS solution	58
28	Forging die hoop stresses, ksi	60
29	Modified gear forging die	61
30	Modified forging die hoop stresses, ksi	62
31	Stock distributions on forged teeth	68
32	Gear machining fixture locating on pitch cone points	69
33	Pinion forging sequence	73
34	Production run forging for die wear evaluation	80
35	Cast set-up for inspection of "A" dimension	81
36	Checking the "B" dimension on a forging	82
37	Checking the "C" dimension on a forging	83
38	Checking the "D" dimension on the electrode	84
39	Marking plane for tooth thickness check on forging	85
40	Measuring tooth thickness of forging	86
41	Measuring whole tooth depths and addendum on forging	87

LIST OF ILLUSTRATIONS (continued)

Figure		Page
42	Plot of dimensional deviations caused by die wear	92
43	Plotted dimensional deviations and extrapolations	93
44	Pinion machining sequence sketches and layout	96
45	Gear machining sequence sketches and layout	97
46	Fatigue test set-up	108
47	Close-up of pinion-gear loading arrangement	109
48	Schematic of pinion loading arrangement	110
49	Bearing pattern of gear teeth	112
50	Summary of strain gage data	116
51	Fatigue test results for cut and forged gear teeth	118
52	Case hardness profiles in cut and forged gear teeth	120
53	Case hardness profiles in cut and forged pinion teeth	121
54	Carburized surfaces of cut and forged test gears	122
55	Carburized surfaces of forged and cut test pinions	123
56	Tooth profiles showing forging flow lines at three locations along a forged gear tooth	125
57	Microstructures in the core of cut and forged gear teeth after final heat treatment	126
58	Comparison of carbide pattern in the hardened case of cut and forged teeth	127
59	Typical fatigue failures in cut teeth showing continuous fracture paths	128
60	Typical fatigue failures in forged teeth showing discontinuous V-shaped fracture paths	129

LIST OF ILLUSTRATIONS (continued)

Figure		Page
61	Photographs of fracture surface at failure initiation sites - a) Top - cut gear tooth b) Bottom - forge gear tooth	131
62	SEM photographs of general fracture surface a) Top - cut gear tooth b) Bottom - forged gear tooth	132
Appendix		
1a	Data sheet for gear data recording	2a
2a	Schematic of set-up to measure "A"	4a
3a	Schematic of set-up to measure "B" and "C" diameters	5a
4a	Schematic of set-up to measure change in spiral angle	7a
5a	Schematic of tooth thickness measurement procedure	8a
6a	Checking equipment required for gear development	9a

LIST OF TABLES

Table		Page
I	Basic Gear and Pinion Dimensions	9
II	Comparison of Production Methods for Spiral Bevel Gears Major Operations	12
III	Candidate Die Material	21
IV	Hot Hardness of Candidate Die Materials	25
V	Rough (R) and Finish (F) EDM Electrode Utilization Schedule	29
VI	Fourth Development Gear Lead Angle EDM Cam Data at 2.500 Radius	35
VII	EDM Process Control Data	36
VIII	Gear Stock Distribution - 1st Lot Forgings	53
IX	Second Development Gear Forging Data	64
X	Third Gear Forging Process Development Run	67
XI	Gear Dimensional Data for Fourth Development Cycle	71
XII	First Run Pinion Forging Process	72
XIII	Forging Parameters for Second Pinion Development Series	75
XIV	Pinion Dimensional Data for Third Development Cycle	77
XV	Third Pinion Development Lead Angle EDM Cam Data at 2.500 Radius	77
XVI	Calculated Pitch Diameter Change with Tooth Thickness Change 22-1/2° Pressure Angle Involute	89
XVII	Dimensional Inspection Statistical Data	90
XVIII	Dimensional Inspection Statistical Data for Gear Fourth Development	91
XIX	Range of Stock Removal	98

LIST OF TABLES (continued)

Table		Page
XX	Stock Removal Record #1	99
XXI	Stock Removal Record #2	101
XXII	Stock Removal Record #3	103
XXIII	Stock Removal Record #4	105
XXIV	Tabulation of Test Fixture Deflections versus Tooth Loading	113
XXV	Direct Labor for Precision Forging Process	134
XXVI	Direct Labor for Conventional Process	136
XXVII	EDM Electrode Utilization	138
XXVIII	Direct and Consumable Tooling Cost for Precision Forging	139
XXIX	Comparative Cost Summary	141

1.0 INTRODUCTION

The fabrication costs for precision high performance spiral bevel gears used in aircraft applications has been an important factor in contributing to the relatively high overall cost of power transmission trains. The production of these critical gears by conventional machining methods appears to have reached a limit as far as improvement in gear performance and unit costs are concerned. New manufacturing approaches are required if significant advances are to be made in improving the cost effectiveness of these highly loaded transmission gears.

The adaptation of present day precision forging technology to gear manufacturing could minimize or eliminate many of the time consuming and costly tooth cutting operations by directly preforming the teeth. This process will produce a metallurgically superior gear, with the teeth semi-finished to a point where it is ready for heat treatment and finish machining. This approach to gear manufacturing is less dependent upon the availability of specialized machine tools, and the skilled labor required to set up and operate them.

This final report summarizes the results of a development program for precision forging integrally formed gear teeth in a spiral bevel gear and pinion design. The objectives of the development program were:

- o Demonstrate the suitability of a mechanical crank press for precision forging a specific gear design with integrally formed teeth.
- o Determine the economics of this forging approach in comparison to conventional processing.
- o Compare the fatigue properties of the forged teeth to the conventionally cut teeth.
- o Develop and document procedures for tool design, tool fabrication and forging for production use.

The cost benefits inherent in the chipless forming of gear teeth have been adequately demonstrated using techniques and materials substantially different from those selected for this program. However, the gears produced by these other chipless forming processes, such as pressed and sintered powder metal gears, molded plastic gears or cold roll formed gears, lack one or more of the characteristics required for outstanding performance of the gear. These typical characteristics are high strength, good fatigue life, wear resistance, efficiency and design flexibility. The precision gear tooth forging process has the potential for producing high performance gears from superior and conventional gear materials. This will result in gears having improved strength and fat'que properties wher compared to conventionally cut gears of the same material and heat treatment.

Advances in die materials, die sinking techniques and forging equipment makes precision forging of gear teeth feasible on a practical production basis. This program does establish the fundementals of the process, technical and economic, based on the actual experience of fabricating a production gear design by precision forging a production quantity. A performance improvement of the forged and finished gears produced on this program has been demonstrated in a limited testing program.

2.0 DESCRIPTION OF GEAR SET, PROCESS AND TOOLING

The design of the CH-47 helicopter gear set, selected for this development and test program, is currently in production and has an extended production schedule. The main transmission spiral bevel gear and pinion for the CH-47 helicopter was selected as the specific components for demonstration of the precision forging process. These gears are mounted in the helicopter transmission nose gear box; transmitting engine power at high rpm to the speed reducing gear train; driving the main rotor. Early in the program the production model of the aircraft was changed from Model A to Model C with an uprating of power and an increase in the size of gear and pinion. This development program was then redirected to the Model C gears. The position of the spiral bevel gear set, selected for development, is shown in a section view of the CH-47 transmission in Figure 1. They are shown assembled in their bearing cartridges in Figure 2. The semifinished gear set is illustrated in Figure 3.

2.1 Specifications for Gear and Pinion

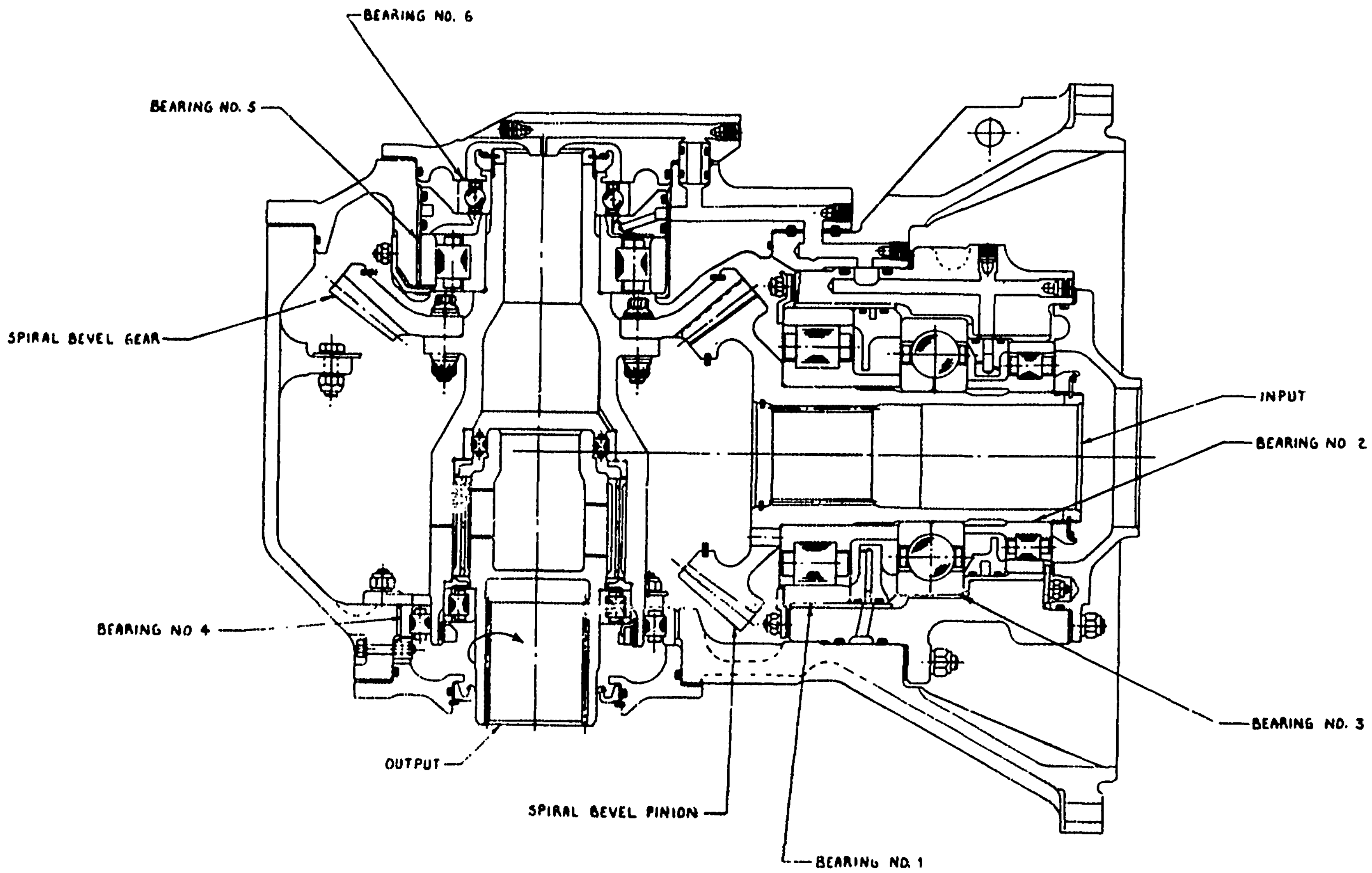
The gear form data, materials, tolerances, finishes and other technical requirements of the drawing have been incorporated in the precision forged gear design. Thus, the evaluation of processing costs and gear performance can be directly compared to the conventionally fabricated gear.

The pinion and gear forging designs SK22269/FR729996 and SK22270/FR629997 respectively are illustrated in Figures 4 and 5. These drawings specify the forging stock left for subsequent finish machining operation. It was the goal of the development program to achieve the dimensional tolerances specified on these drawings. Basic gear and pinion drawing dimensions are tabulated for convenience in Table 1. The comparable Boeing-Vertol part numbers are also shown in the table.

The input pinion operates at 14,720 rpm transmitting 3750 H.P. developing a pitch line torque of 16,056 in pounds and is expected to sustain 1100 hours of operating time between overhauls. The calculated design maximum tooth bending stress is 29,000 psi with a tooth contact stress of 205,000 psi. The design load per tooth is 4523 pounds. These performance requirements are responsible for the high quality and reliability specifications which must be met by these components.

2.2 Process Design

The technique for the precision forging of integrally formed gear teeth is based on the use of a modified crank press. The Maxipres a product of National Machinery Company, is a conventional design single-action mechanical crank press which has been used for precision production forging



SECTION THRU ℄

Figure 1. Cross section of the CH-47 transmission nose gear box.

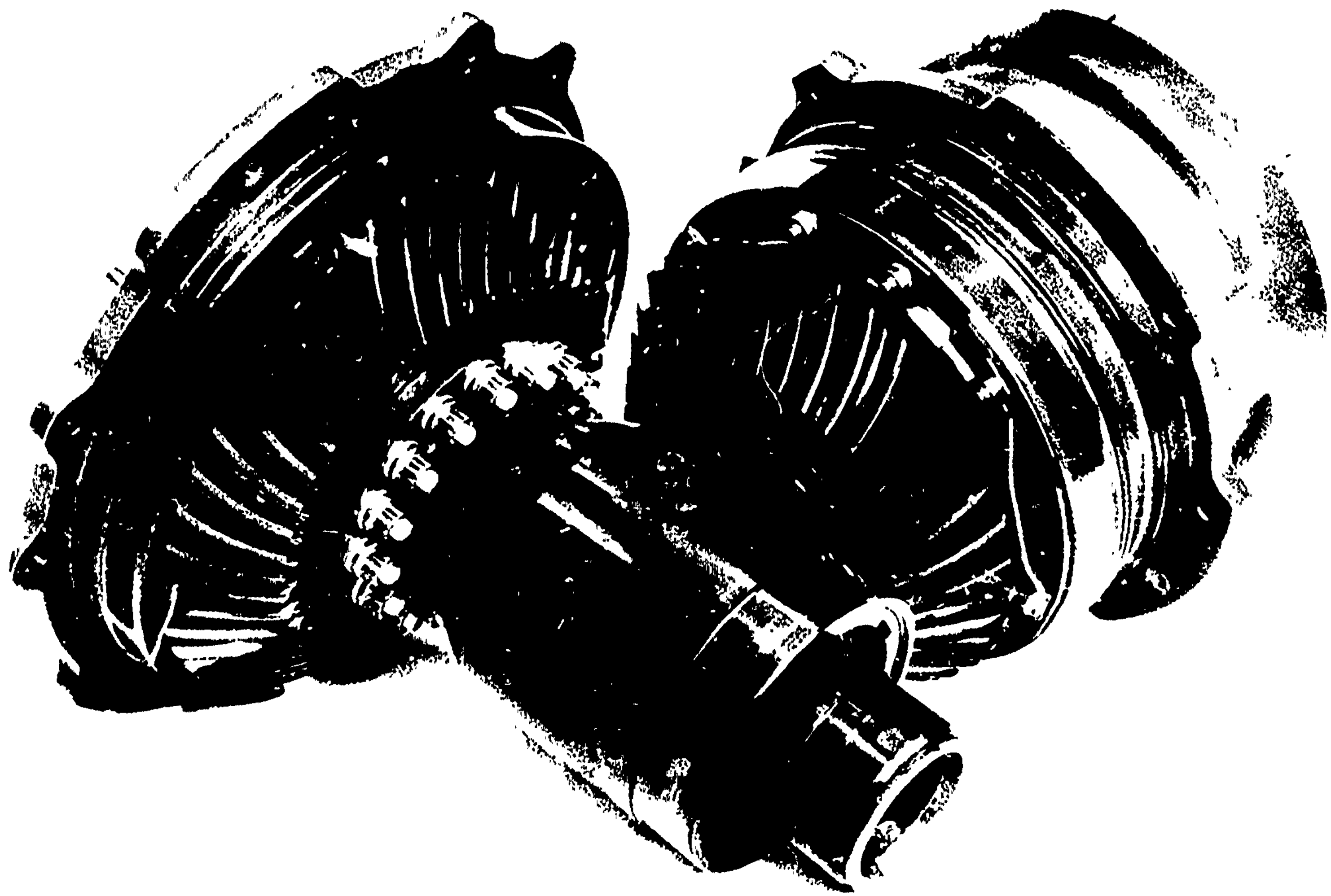


Figure 2. Spiral bevel gear set assembled in bearing cartridges.

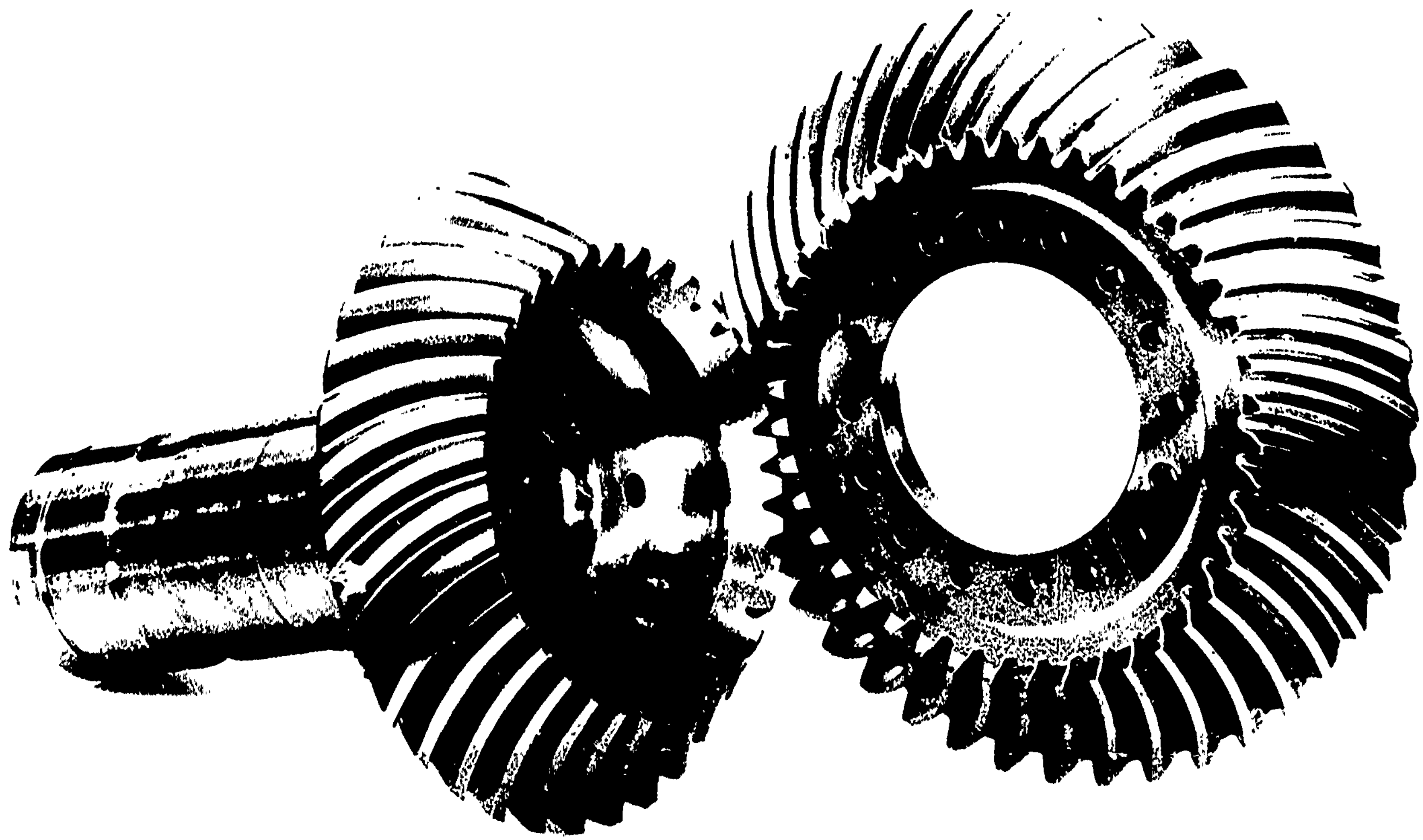
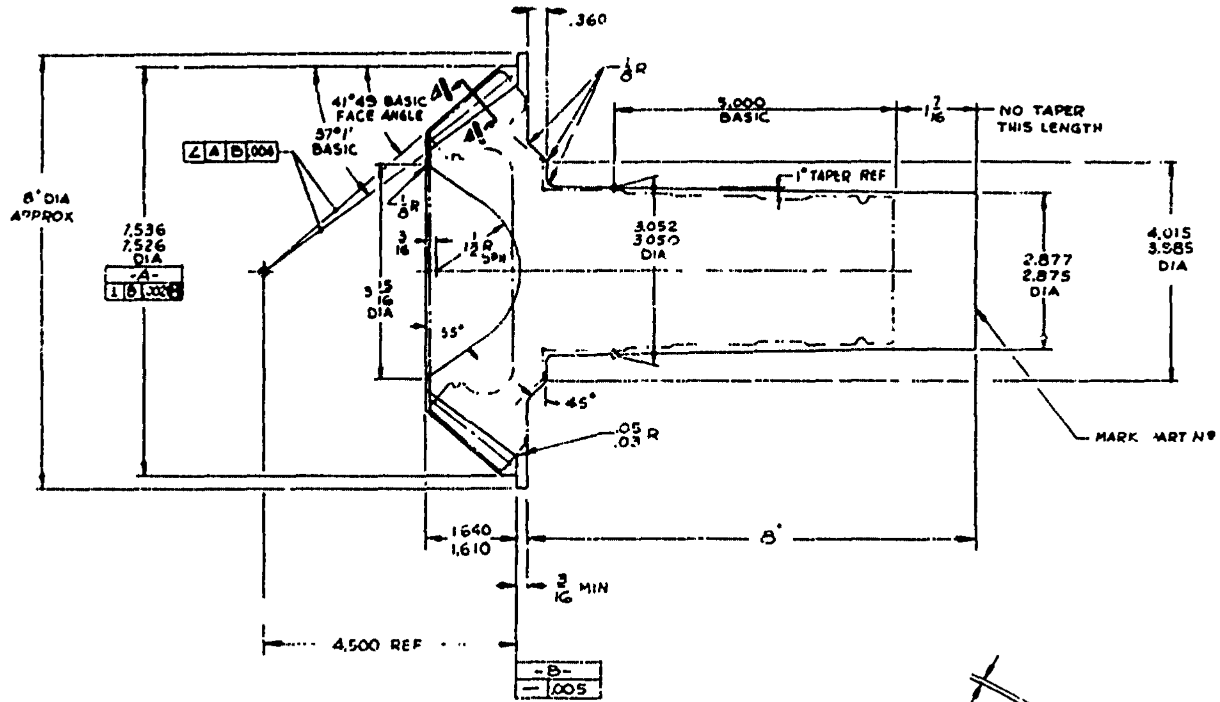
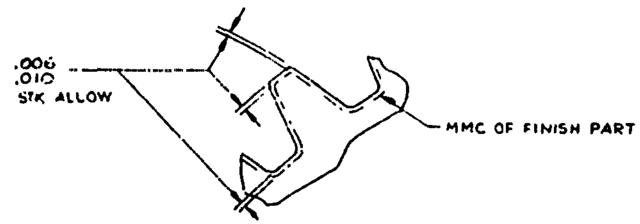


Figure 3. Semi-finished spiral bevel gear and pinion set. Boeing-Vertol CH-47 helicopter nose box transmission.



SPIRAL BEVEL GEAR DATA	
NUMBER OF TEETH	35
PITCH	4.930
PRESSURE ANGLE	22° 30'
SPIRAL ANGLE (MEAN)	25° 0' LH
PITCH DIAMETER A .003 DIA	7.099
SHAFT ANGLE BASIC	90°
PITCH ANGLE BASIC	39° 9'
ROOT ANGLE BASIC	37° 1'
FILLET RADIUS	.045 - .055
PITCH TOLERANCE	.0003
TOTAL INDEX TOLERANCE	.0015
BACKLASH CONTRIBUTION OF GEAR WITH ZERO BACKLASH MASTER (NORMAL)	.003 - .006
WHOLE DEPTH	.383 - .393

REFERENCE DATA	
CIRCULAR TOOTH THK @ P D	.334 - .337
ADDENDUM	.199
DEDENDUM	.184
NORMAL CHORDAL THK @ P D	.287
NORMAL CHORDAL ADDENDUM	.197
BACKLASH WITH MATING GEAR ON STANDARD MOUNTING DISTANCE (NORMAL)	.006 - .012
NUMBER OF TEETH IN MATING GEAR	43
LOAD SIDE OF TOOTH	CONCAVE



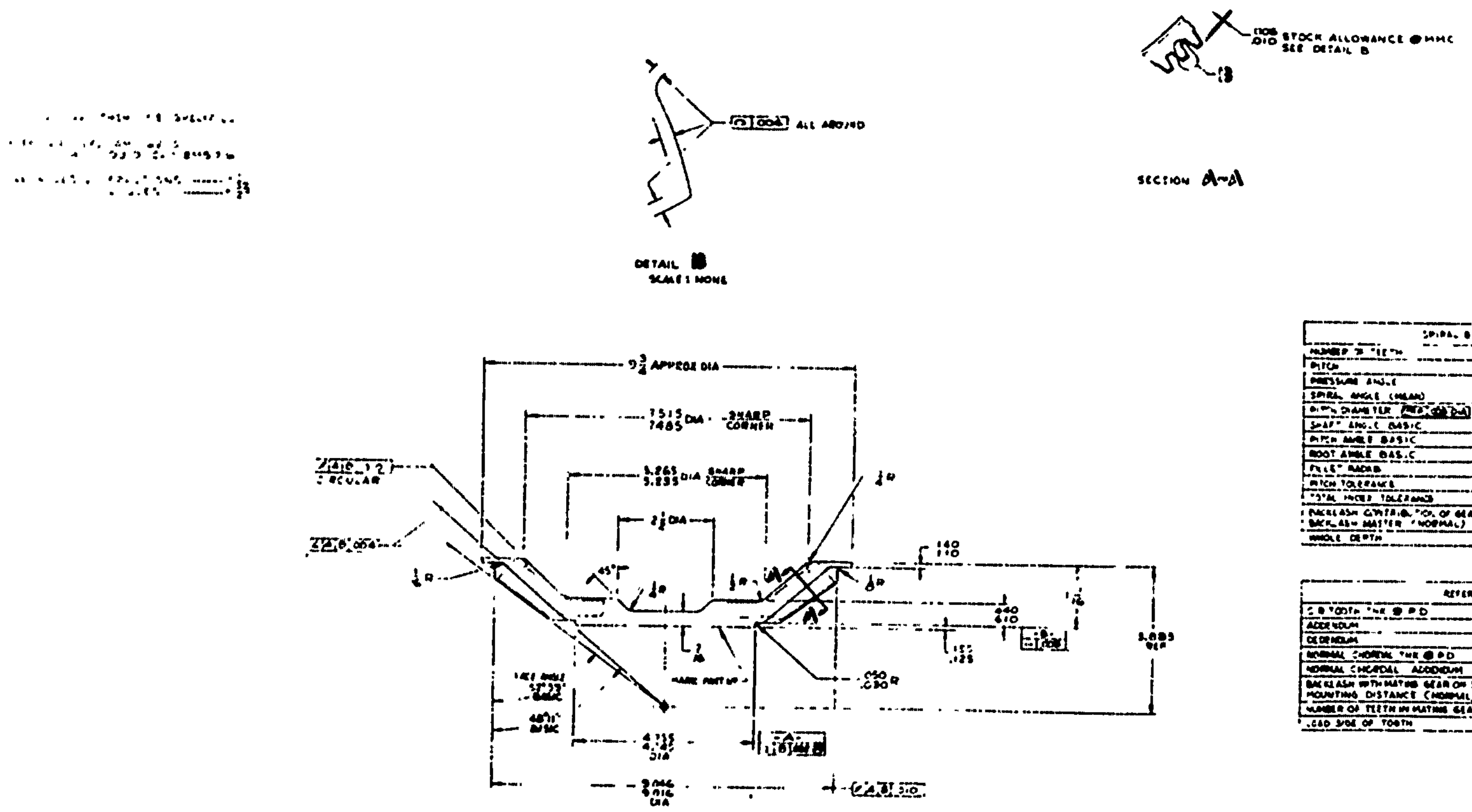
SECTION A-A
SCALE: NONE

NOTES UNLESS OTHERWISE SPECIFIED

1. MATERIAL: STEEL AMS 6265
AISI 9310 CVM-BMS 7-6

2. TOLERANCES: FRACTIONS —— $\pm \frac{1}{32}$
ANGLES —— $\pm 2°$

Figure 4. Pinion forging design.



SPIRAL BEVEL GEAR DATA	
NUMBER OF TEETH	43
PITCH	4930
PRESSURE ANGLE	22°30
SPIRAL ANGLE (MEAN)	25°0' RH
PITCH DIAMETER [illegible]	8 722
SHAFT ANGLE BASIC	90°
PITCH ANGLE BASIC	50°51
ROOT ANGLE BASIC	48°11'
FILLET RADIUS	.045-.035
PITCH TOLERANCE	0003
TOTAL INDEX TOLERANCE	0015
BACKLASH CONTROL [illegible] OF GEAR WITH ZERO BACKLASH MASTER (NORMAL)	003-006
WHOLE DEPTH	388-393

REFERENCE DATA	
C R TOOTH THK @ P D	284-.294
ADDENDUM	.146
DEDENDUM	237
NORMAL CHORDAL THK @ P D	241
NORMAL CHORDAL ADDENDUM	144
BACKLASH WITH MATING GEAR ON STANDARD MOUNTING DISTANCE (NORMAL)	.006-012
NUMBER OF TEETH IN MATING GEAR	35
LEAD SIDE OF TOOTH	CONVEX

Figure 5. Gear forging design.

Table I

Basic Gear and Pinion Dimensions

Spiral Beven Gear and Pinion Data	Pinion SK22269	Gear SK22270
Boeing Vertol Part Number	114D-6244	114D-6245
Number of Teeth	35	43
Pitch	4.930	4.930
Pressure Angle	22°30'	22"30'
Spiral Angle (mean)	25°0" L.H.	25°0" R.H.
Pitch Diameter	7.099	8.722
Pitch Angle (basic)	39°9'	50°5'
Root Angle (basic)	37°1'	48°11'
Face Angle	41°49'	52°59'
Circular Tooth Thickness	.344-.337	.291-.294
Addendum	.199	.146
Dedendum	.184	.237
Normal Chordal Thickness at P.D.	.287	.241
Load Side of Tooth	Concave	Convex

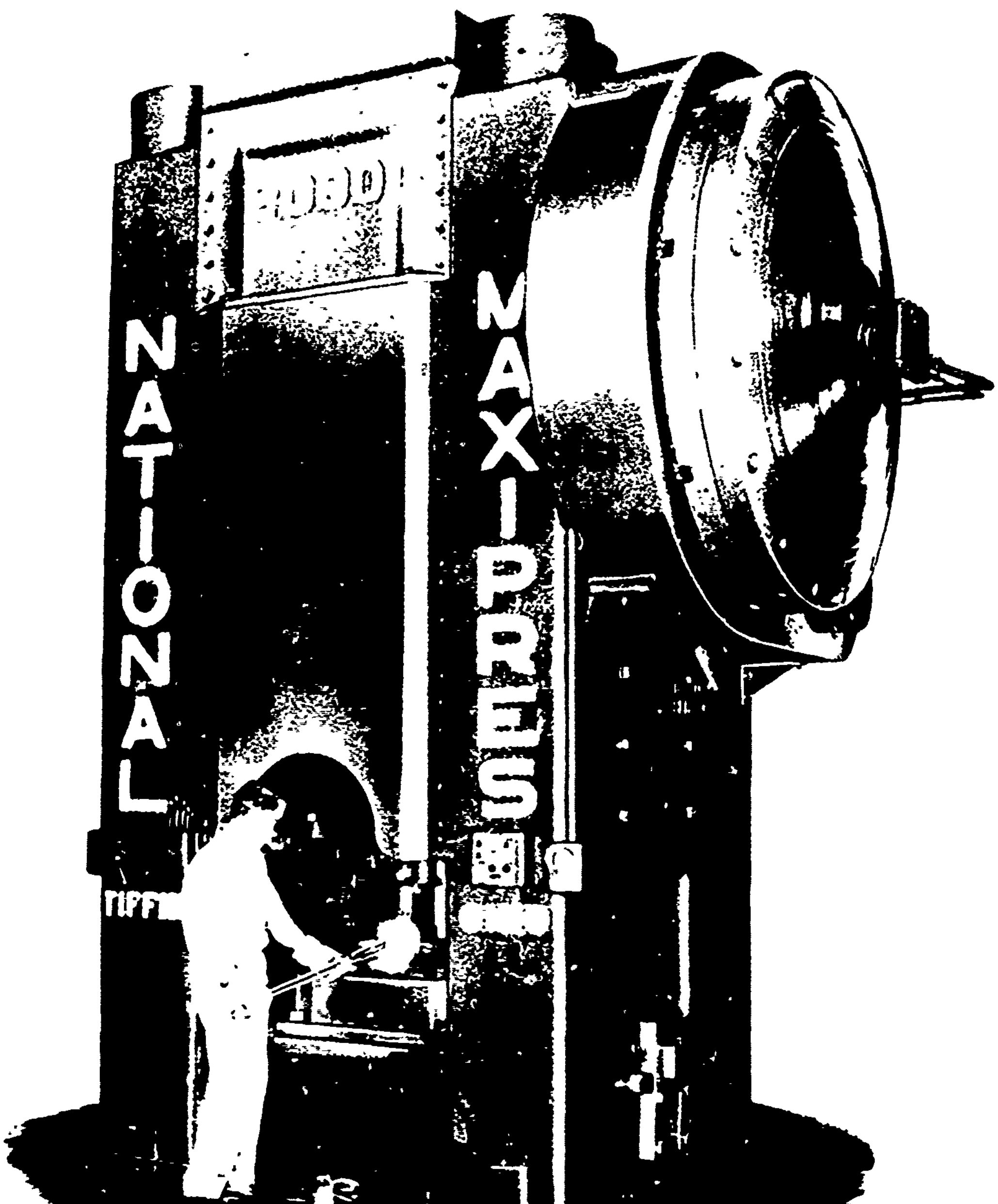
for over 30 years and is widely available in industry (see Figure 6). It is capable of high-speed production of forgings. Production tolerances on selected dimensions can be held to a few thousandths of an inch. A typical forged part is produced in this press in one or more preform blows and a coining blow. The several operations may be accomplished simultaneously at each cycle of the press. This multi-blow method is usually chosen, even though the press may have sufficient energy to forge the part in one blow, to allow the use of small diameter stock. The relatively small diameter starting material can be more accurately and economically cut into billet lengths which can then be upset to produce preformed forgings of larger diameter prior to a final coining operation. The additional hot working of the billet can further enhance the final properties while redistributing the material to a more ideal location for the final configuration. The inherent ability of the mechanical crank press design to forge to close tolerances was considered in the decision not to "green grind" the forged teeth prior to gear carburizing.

With the mechanical crank press die life is enhanced by the relatively low ram velocity. Two of the principal factors which contribute to better die life are the restrictions of metal velocity (1) in the die and close control of die temperatures. High metal velocity along die surfaces causes erosion and loss of dimensional control and section deformation. The desirable flow around the projections in the die is attributed to the moderate speed of the descending ram in mechanical press operations (2).

Consideration was given for the need to "green grind" the forged teeth before carburizing to correct dimensional discrepancies. The addition of such a corrective operation would have been contrary to the objectives of the program and therefore no provision was made for this redundant process. The comparison of conventional and proposed major process operations is shown in Table II.

The exact effect of the as-forged surface condition on the formation of the carburizing layer was the subject of investigation during the program. At this time metallurgical inspection of precision forged teeth appears to indicate a good probability of successful carburizing without removal of surface material. Prior experience also indicates that a more diffused carbide network is usually achieved when hot worked structures are carburized. This phenomenon is generally attributed to the tendency toward grain refinement associated with the hot forging process.

A more detailed forged gear process routing, Figure 7, was established to guide the specific detailed manufacturing operations. The actual forging deformations were planned so as to divide the work performed in forging into two approximately equal increments. This was done empirically be estimating two volume/flor distance relationship shown in the successive forms in Figure 8. Then the detail design was done for the forging tooling, based on the forging dimensions and sequence, and the press dimensions.



2,000-TON MAXIPRES

Figure 6. Rigid frame single crank type mechanical press used for close tolerance forging of spiral bevel gears.

Table II

Comparison of Production Methods for Spiral Bevel Gears Major Operations

Present Method	Planned Method
Closed Die Forging of Gear Blank	Precision Forged Gear Blank with Teeth
Preliminary Process Machining of Gear Blank	Process Machine Gear
Generate Semifinished Gear Teeth	Carburize and Heat Treat Gear
Carburize and Heat Treat Gear	Process Machine Gear
Process Machine Gear	Finish Grind Gear Teeth
Finish Grind Gear Teeth	Final Inspect Gear
Final Inspect Gear	

MANUFACTURING ROUTING WORK SHEET

PART NAME	CUSTOMER PART NO	F.R. NO	SFX
Gear, Spiral Bevel	SK 222	7299	0h

CUSTOMER NAME	PREP BY	PAGE
Boeing	RWP	1 of 1

DESCRIPTION OPERATION OR MATERIAL	T	OPER. NO OR MAT'L CODE & QUANT	SKETCH OR COMM	F.R. NO	SFX	OCCUP CODE	DIV	DEPT	OP.	CT PT	REQ. NO	E.C.B NO. OR MAN HRS PER 100 PCS.	TOOL-CUST REV OR MCH HRS. PER 100 PCS.	CODE	MACH. CODE
AMS-6265															
3-1/2 DIA. x 5-7/8															
CUT STOCK TO LENGTH		10	10												
DOALL SAW															
CHAMFER ENDS	T	20	20				6	23	63						
GARDNER POLISHER															
HEAT	T	30	30				6	23	11						
PREFORM															
WARM COIN															
2000 TON MAXI PRESS															
ROTARY FURNACE															
EXO-GAS															
ZIRC BLAST		40					6	55	12						
PANGBORN BLAST ROOM															
REMOVE FLASH		50	50												
WARNER & SWASEY															
LATHE															
DEGREASE		60					6	23	63						
DETREX DEGREASER															
COLD COIN	T	70	70				6	23	11						
2000 TON MAXI PRESS															
ZIRC BLAST		80					6	55	12						
PANGBORN BLAST ROOM															
MAGNAFLUX INSPECT		90					6	23	91						
MAGNAFLUX UNIT															
DEMAGNETIZE		100					6	23	91						
MAGNAFLUX DEMAG															
FINAL INSPECTION	T	110	110				6	23	91						
BENCH-GAGES															
OIL		120					6	23	91						
TANK															
BOX															
SHIP															

1) INDUSTRIAL ENGR ______ 5) PRODUCTION CONTROL ______
2) PLANNING ENGR ______ 6) ACCOUNTING DEPT ______
3) QUALITY CONTROL ENGR ______ 7) METALLURGY LAB ______
4) QUALITY CONTROL N.D.T ______ 8) CHEMICAL LAB ______

Figure 7. Gear forging process layout.

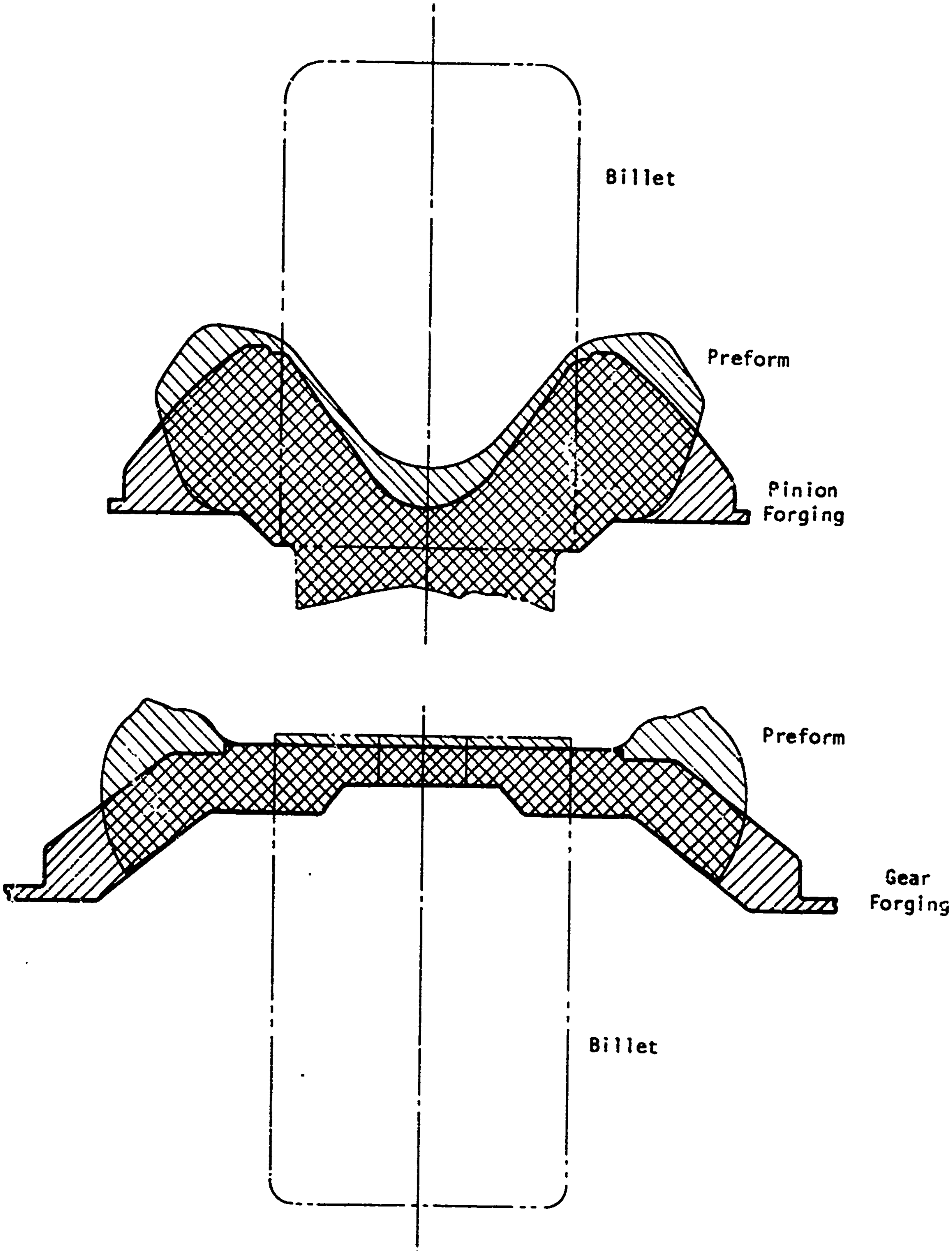


Figure 8. Billet and preform layouts.

2.3 Gear Forging Tool Design

The designs of the gear preform and hot coining tools are illustrated in Figure 9. In the preforming operation, the starting billet is converted from a 3-1/2 diameter x 5-1/2 long cylinder to a flat conical disc approximately 9 inches in diameter and 1-3/4 inches long. The starting billet is manually positioned in a recessed locating seat for preforming, to achieve centrality, and to assure an even distribution of material in the preform. The preform die cavity is machined with the conical surface in a downward direction and with the parting line near the top of the part so that any unevenness in filling, which may still occur, will be at the extreme rim of the blank. Later the material in the rim moves into the flash area which is external to the location of the gear teeth. Having the conical surface facing downward also facilitates forming a small conical indentation in the upper surface to serve as a centrality locator for positioning the preform in the hot coining station. A smooth flow of material radially outward is achieved as the starting billet is compressed in an axial direction.

Draft angles were selected so that the preform would be retained in the lower die cavity on the upstroke of the press. It is then lifted from the die by a pneumatically actuated ejector pin to facilitate removal and transfer to the hot coining station by the operator. The preform is turned over and placed on the locator in the hot coining die. The lower die block is of completely open design to permit rapid placement and centering of the preformed part so that sufficient residual heat can be maintained. This is an important processing feature because accomplishing both the preforming and coining operations during the same heating cycle minimizes the exposure for metallurgical deterioration of the surface material.

The profile of the lower hot coining die was made to match the profile of the preform punch when the hot coining die is in a fully closed position. When the coining die is in the open position there is an intentional mismatch due to the protrusion of the central locating pin. This mismatch accomplishes two objectives. It permits the larger conical surface to function as a "rough" locator while the pin itself serves as a final locator. Secondly, it supports the hot preform a short distance above the die block and this prevents excessive heat loss via this sink. After the coining operation is completed, and as the dies separate, the pin is instantaneously actuated by means of a mechanical spring. A fast response would be desirable in all cases and is essential in the case of a spiral bevel gear or pinion forging when a negative draft condition exists in the tooth portion of the die. Failure to achieve an immediate release of the forging from the lower die block as the press ram starts on the upstroke could result in the stripping of the teeth from either the die or the forging, probably the latter.

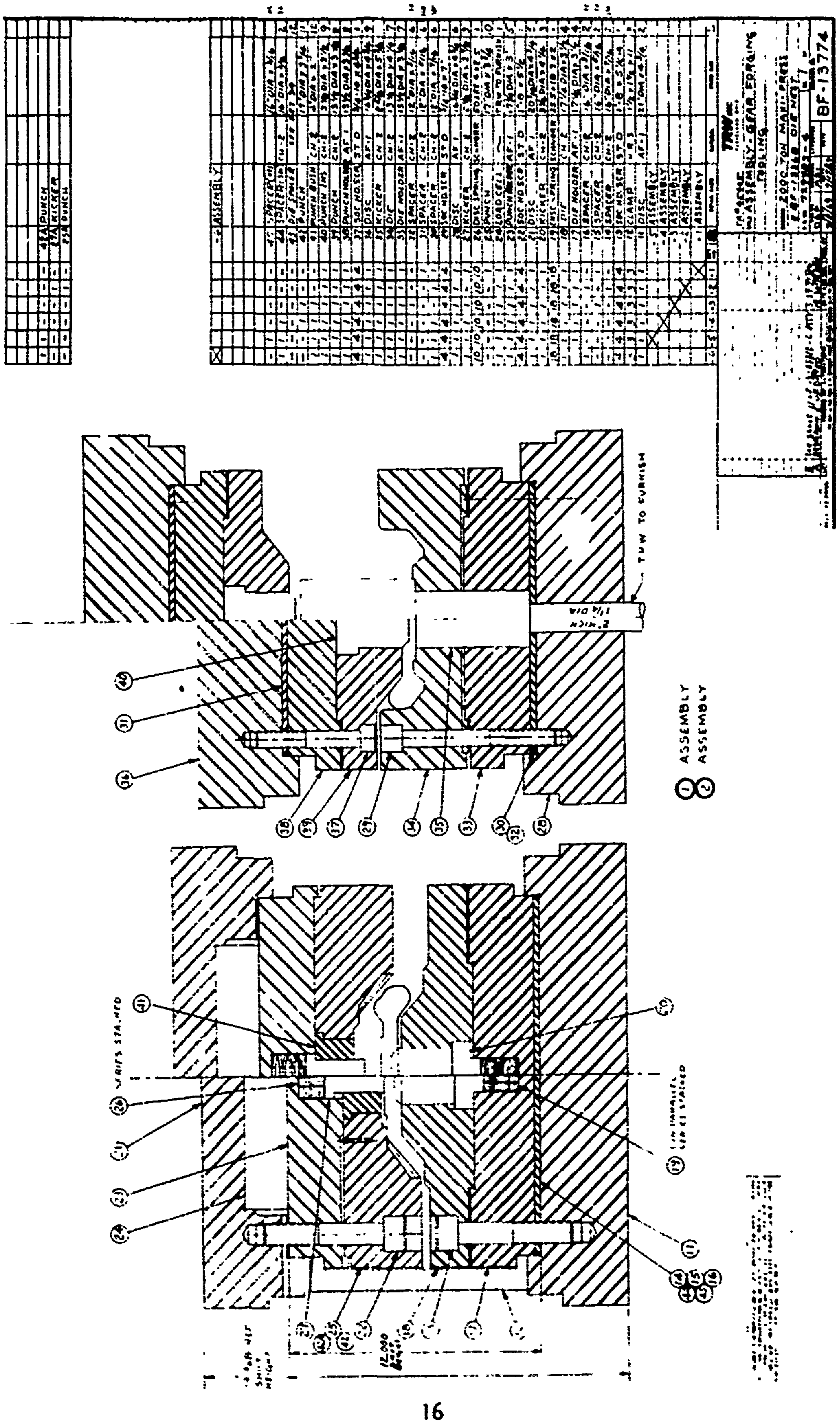


Figure 9. Design layout for gear preform and hot coin forging tooling.

A second spring actuated pin is used to shed the forging from the upper die (punch) an instant after the forging is released from the lower die block. To shed the forging from the punch requires a slight rotation of the forging which can only be accomplished after the holding friction on the lower surface has been overcome. Therefore, the balance between the spring forces of the opposing stripper pins is critical in order to have them function in the proper sequence.

It is estimated that a billet temperature in excess of 2000°F would be necessary to provide sufficient plasticity to achieve an acceptable fill in the tooth portion of the gear forging. With this billet temperature it was anticipated that at the moment of impact certain portions of the die surface could reach a temperature near 1300°F. Prolonged contact between the hot billet and the die would have a deleterious effect on die life. To minimize the contact time for the most critical elements of the tooling, the tooth form was designed into the punch portion of the die set. Thus, any delay which might be encountered after placing the preformed billet in the hot coining station would not result in a transfer of heat to the tooth portion of the cavity. Furthermore, on the upstroke of the press, gravity and the inertia of the forging, in addition to the force imparted by the spring stripper, contribute to freeing the forging from the cavity.

2.4 Pinion Forging Tool Design

The design of the forging tooling for the spiral bevel-pinion (see Figure 10) was approached the same as for the gear. The pinion configuration is more complicated than that of the gear due to the integral shaft or stem on the pinion. This in effect increases the number of forging operations required to transform the material from a starting billet shape into the final pinion forging configuration. It was estimated that a minimum of three forging operations would have been necessary to do this. It was possible to eliminate one of these operations in the development program by machining the first preform shape from the bar material. This appreciably reduced the forging tooling cost and time required to develop the forging. The pinion process routing is shown in Figure 11.

For the small number of pieces involved in this program the extra upset forge tooling could not be justified economically. The design of tooling for the preforming and hot coining stations is illustrated in Figure 10. In the preforming operation the portion of the billet protruding above the lower die is converted from a 3-1/2 inch diameter x 5-1/2 long cylinder to a flat conical disc approximately 7 inches in diameter by 2 inches thick. Positioning of the billet is very easy because the geometry of the stem on the billet is less than the depth of the die cavity and has a matching taper. In this way the positioning of the billet is as accurate as the centrality of the stem on the billet. The geometry of the locating cavity in the coining station also matches the tapered stem of the billet and will thus again assure centrality.

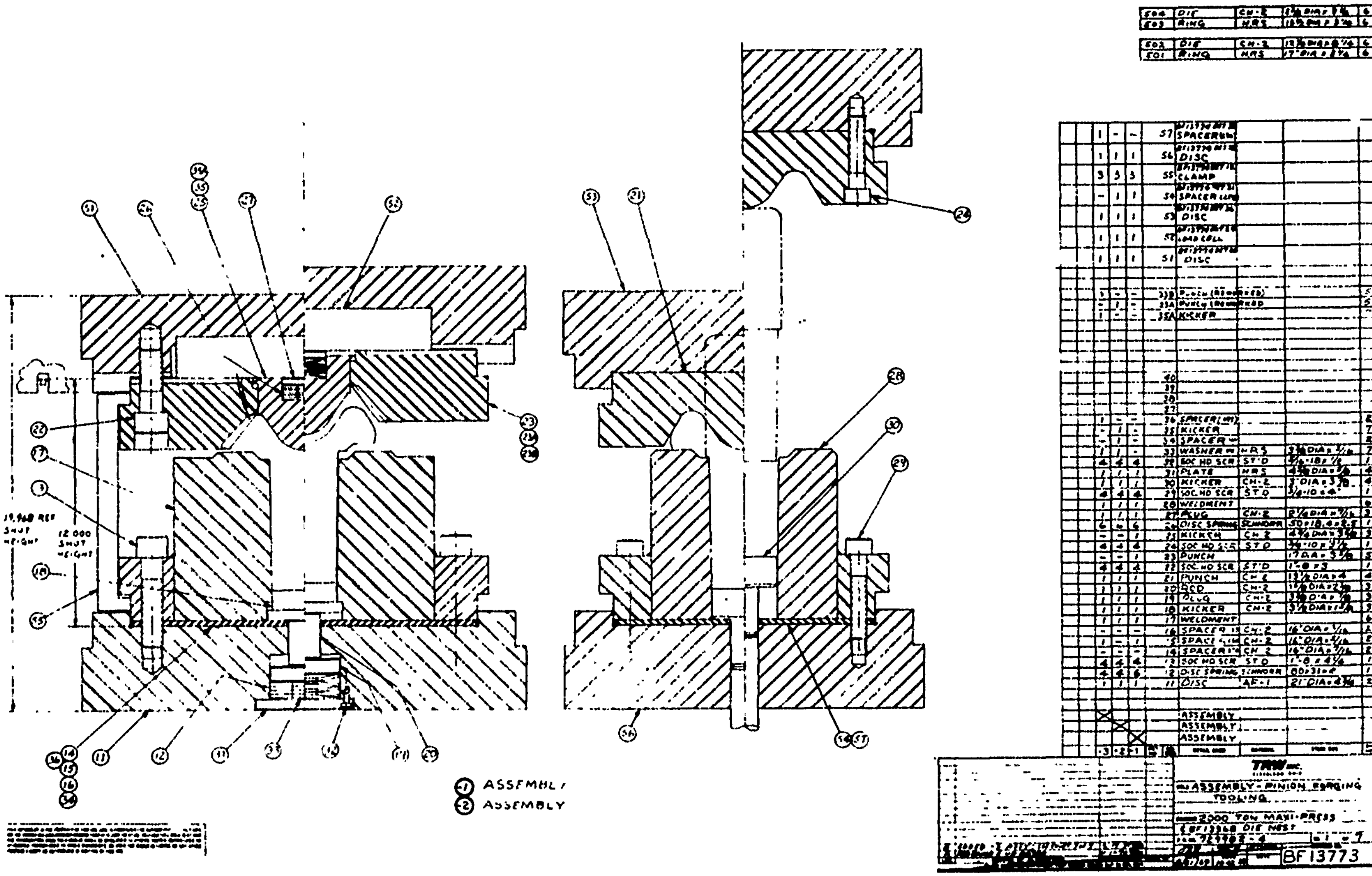


Figure 10. Pinion forging tool drawing.

MANUFACTURING ROUTING WORK SHEET

PART NAME	PINON,SPIRAL BEVEL
CUSTOMER NAME	BOEING
CUSTOMER PART NO.	SK 22271
P.R. NO	729982
PREP BY	RVP
PAGE	1 of 1

DESCRIPTION OPERATION OR MATERIAL	T	OPER. NO. OR MAT'L CODE & QUANT	SKETCH OR CHEM	P.R. NO	OCCUP. CODE	DIV	DEPT	GP	CT. PT	SEQ. NO.	E.C.A. NO OR MAN HRS. PER 100 PCS.	TRIM-CUT REV. OR MCH. HRS. PER 100 PCS.	MACH CODE
AMS-6265													
CUT STOCK TO LENGTH		10	10										
DOALL SAW													
MACHINE SLUG		20	20										
WARNER & SWASEY													
LATHE													
HEAT	T	30	30			6	23	11					
PREFORM													
WARM COIN													
2000 TON MAXI PRESS													
ROTARY FURNACE													
EXO-GAS													
ZIRC BLAST		40				6	55	12					
PANGBORN BLAST ROOM													
REMOVE FLASH		50	50										
WARNER SWASEY													
LATHE													
DEGREASE		60				6	23	63					
DETREX DEGREASER													
COLD COIN	T	70	70			6	23	11					
2000 TON MAXI PRESS													
ZIRC BLAST		80				6	55	12					
PANGBORN BLAST ROOM													
MAGNAFLUX INSPECT		90				6	23	91					
MAGNAFLUX UNIT													
DEMAGNETIZE		100				6	23	91					
MAGNAFLUX DEMAG													
FINAL INSPECTION	T	110	110			6	23	91					
BENCH - GAGES													
OIL		120				6	23	91					
BOX													
SHIP													

1) INDUSTRIAL ENGR. ______ 5) PRODUCTION CONTROL ______

2) PLANNING ENGR. ______ 6) ACCOUNTING DEPT ______

3) QUALITY CONTROL ENGR. ______ 7) METALLURGY LAB ______

4) QUALITY CONTROL DEPT. ______ 8) CHEMICAL LAB ______

Figure 11. Pinion forging process layout.

Practically all of the heat loss to the dies will be from the stem of the billet. Since, no planned deformation occurs in the stem, a heat loss here does not appear to create a problem. The upper dies at both the preform station and the coining station will be in contact with the hot forging for a very short period of time. This favorably limits the heat transfer to the critical part of the tooling containing the gear tooth configuration.

Due to the combination of geometric factors such as pitch, cone angle, spiral angle and depth of gear tooth, there is negative draft angle in the axial direction on the end portions of the pinion tooth. This negative angle prevents the pinion from being withdrawn from the die in a purely axial direction without an accompanying rotational motion. Thus, unless the pinion is free to rotate, the upward motion of the punch would deform or otherwise damage the gear teeth. To allow the forging to rotate, the release in the lower die must act immediately as the ram starts to move past bottom dead center. A heavy duty spring activated stripper pin is provided in the lower die for this purpose. It must have sufficient force to overcome the frictional resistance of the slightly tapered die wall plus the weight of the forging plus the force of the shedder pin in the upper die. The stripper and shedder pins are designed to have a very small movement since only a slight displacement of the forging away from the tapered die wall is necessary to break the frictional holding force and allow the forging to rotate. Therefore, the spring movement is kept small so that a large preload can be used to achieve a high release force almost instantaneously as the ram starts its upstroke.

The proper sequence for ejecting the forged part is to have a release from the lower die first and shortly thereafter to have the forging spin free from the upper die. If this occurs in rapid sequence, the forging will drop back into the lower die cavity but will remain free to be lifted out by the press operator. This action would retain the forging in an upright position and prevent damage of the pinion teeth.

2.5 Die Material Selection

A die surface temperature of approximately 1300°F was expected at the moment of impact with the forging, therefore the selection of a suitable die material is critical. An initial list of candidate materials (Table III) was compiled on the basis of chemical composition and a history of satisfactory performance in other high temperature applications.

In a previous evaluation (3) of the wear resistance of a limited number of hot work die materials for a spur gear forging die application, a reasonable correlation was found to exist between measured hot hardness and die performance. The die design used for that study was a medium pitch (D.P. = 16), small spur gear approximately 1-1/4 inches in diameter and 2 inches long. Die inserts and hot hardness specimens were prepared for the series of available die materials. The dies and corresponding hardness specimens were heat treated to manufacturers specification and resulting room temperature hardnesses were measured. Hot hardness values at 1100°F

Table III

Chemical Composition of Candidate Die Material

Alloy Designation	Producer	Detail No.	C	Cr	Mo	W	V	Co	Other
WMD Extra	Bohler	1	0.33	2.90	2.90	-	0.50	3.00	
WW Hotwork	Vanadium Alloys	2	0.30	12.00	-	12.00	1.05	-	
Rex 49	Crucible	4	1.10	4.25	3.75	6.75	2.00	5.00	
W-9	Dorrenberg	5	0.30	2.65	-	8.50	0.35	-	
W-11-C	Dorrenberg	6	0.30	2.40	-	8.50	0.25	2.00	
Bearcat (S-7)	Republic	7	0.50	3.25	1.40	-	-	-	0.7Mn, 0.3Si
QRO-45	Fagersta	8	0.30	2.80	2.80	-	0.50	2.80	
HSM	English Steel Corp.	9	0.30	2.85	-	10.00	0.35	-	
HD.3MX	English Steel Corp.	10	0.33	3.00	2.80	1.00	0.90	3.00	0.90Si
Congo HW	Braeburn Steel	11	0.10	3.50	5.00	4.00	0.50	25.00	
H-23	Braeburn Steel	12	0.30	12.00	-	12.00	-	-	
T-6	Braeburn Steel	13	0.80	4.25	0.75	18.00	2.00	11.50	
M-6	Braeburn Steel	14	0.80	4.00	5.00	4.00	1.50	12.00	
MA	Kind Co. (German)	15	0.30	2.65	-	8.50	0.35	-	
MA Supra	Kind Co. (German)	16	0.30	2.40	-	8.50	0.25	2.00	
J-46	Jessop	17	Not Available						
W 99	Witten	18	0.30	2.50	-	8.50	0.40	-	
Marathon Special W	Marathon	1a	0.30	2.70	-	9.00	0.35		0.2Si, 0.3Mn
Tropic AZ	Osbourn	2a	0.30	3.25	-	8.50	0.25		
Tropic AZN	Osbourn	3a	0.25	3.00	-	8.50	0.25	-	2.25Ni
W-99	Witten	4a	0.30	2.50	-	9.50	0.40		
Mod 1900	TRW Metals Division	5a	0.11	10.30	-	9.00	-	10.00	1.50Cb, 1.00Ti, 6.30Al, 0.03B
H-26	Latrobe	6a	0.50/ 0.65	3.75/ 4.25	-	17.50/ 18.50	0.85/ 1.15	0.11	0.1/0.4Mn 0.1/0.4Si
H-26	Crucible	7a	0.50/ 0.65	3.75/ 4.25	-	17.50/ 18.50	0.85/ 1.15	0.11	0.1/0.4Mn 0.1/0.4Si
Calmax	Uddeholm	8a	0.28	11.50	-	7.5	0.55	9.50	
Haynes 6B	Haynes	9a	1.00	30.00	1.5	4.25	-	Bal.	3.0Fe, 3.0Ni, 2.0Si, 2.0Mn
FERRO-TIC CM	Sinter Cast	10a							TiC in Cr Tool Steel Matrix
FERRO-TIC	Sinter Cast	11a							TiC in Ni-Base Matrix

were also obtained and plotted against the observed die wear which was determined by measuring the inside diameter of each forging die after a 500 piece forging run. As expected, an inverse relationship shown in Figure 12 was obtained between measured die wear and hot hardness.

It is not known whether a similar relationship exists for spiral bevel gear forging dies since there are a number of design and process parameter variations for these two parts. Major differences exist in the size of the gears, gear type, gear tooth coarseness, blank configuration, die des'gn, method of loading and ejection, method of heating and size of forging equipment required. These many differences may effect the linearity of the hot hardness versus wear relationship but it would be reasonable to assume that an inverse relationship will prevail. Therefore, as an aid in selecting a material, hot hardness values at 1100°F and 1200°F were obtained for each of the candidate materials (Table IV).

In addition, factors such as impact resistance, machinability, availability, heat treatment procedures and price were assessed. Based on hot hardness alone, the candidate die materials were ranked as follows:

Materials	Brinell Hardness at 1200°F
1. FerroTic* (HT6)	401
2. Mod 1900* Ni Base	363
3. Latrobe H-26	352
4. Special** H-21 (Mod)	311
5. Uddeholm* Calmax	269
6. FerroTic (CM)	285
7. Witten** H-21 (Mod)	285
8. Allegheny Ludlum H-21	255

* These materials are not available in required size except on special order.

** Imported materials, long lead time required on large bar sizes.

The most readily available, domestic, high performance, hot work die steels are H-26 and H-21. The H-26 material exhibits superior hot hardness but is less impact resistant than H-21 steel.

Coining dies were fabricated from both H-26 steel and H-21 steel. Because of its higher hot hardness, the H-26 die was evaluated first. The wear resistance of H-26 was expected to be superior to that of H-21. The H-21 die was available as backup in developing the proper gear form configuration if the H-26 die were to fail by fracturing.

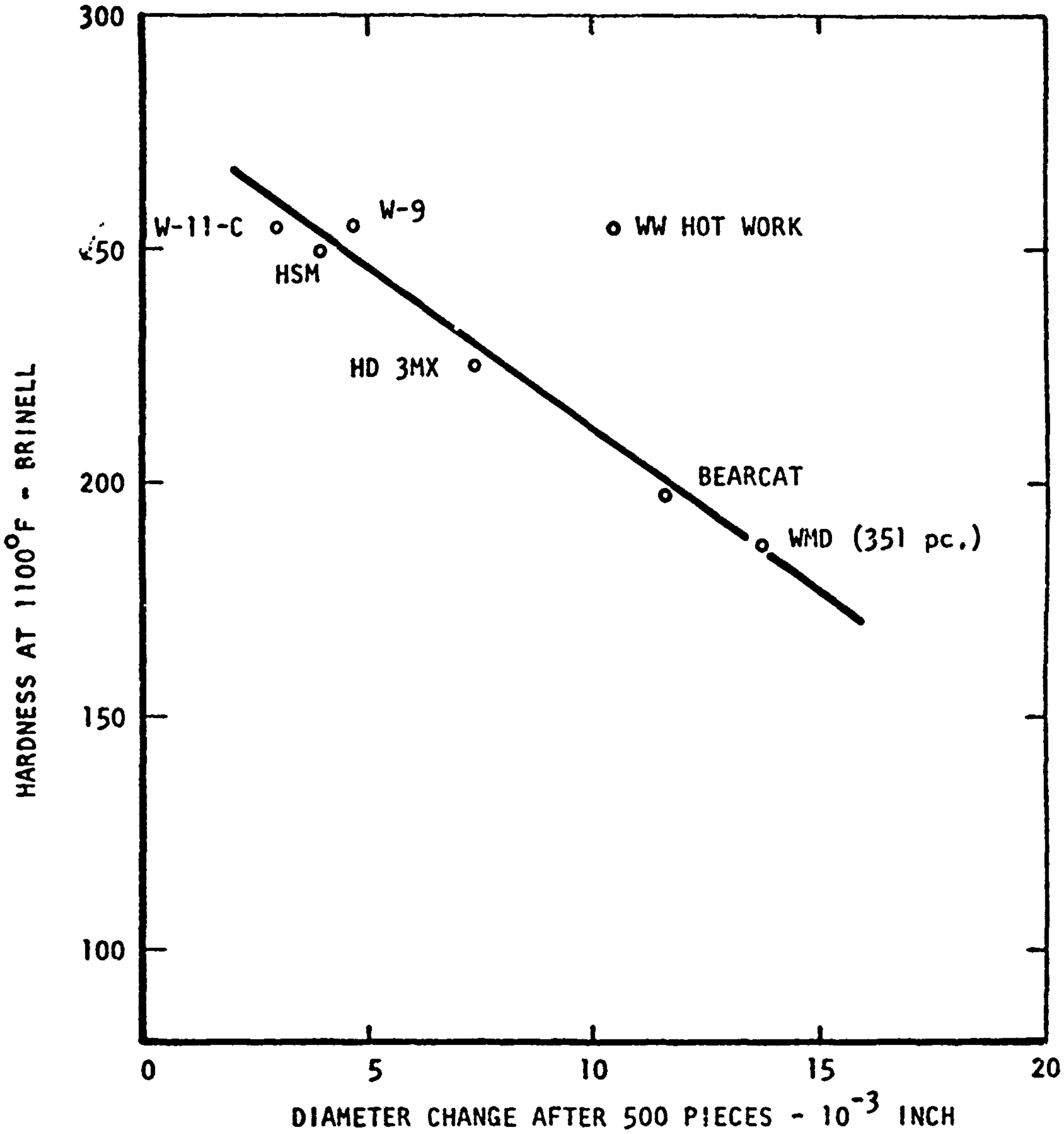


Figure 12. Die diameter change after 500 pieces.

Readily available conventional hot work die materials AF-1 and CH-2 were used in the fabrication of the preform forging dies and for the less critical components of the hot coining tooling.

The die materials, in Table IV, indicated by the asterisk, were procured and used for hot forging in this program. The service results are presented in Sections 4 and 5. The heat treatment was performed on the die blanks after they were rough and semifinished, leaving only the gear form cavitation and finish surface grinding or the end faces to be done on the hardened dies.

The heat treatment initially performed on the dies followed the material suppliers recommended schedule of preheating to 1100°F, austenitizing at 2150°F for 1 hour and oil quenching, followed immediately by double tempering the H-21 at 1000°F and the H-26 at 1100°F for 4 hours. This treatment was slightly modified on subsequent dies to favor toughness. The final hardness reading was not affected by the modified heat treatment performed as follows:

1. Stress relief - 1100°F 1 hour in neutral salt, air cool.

2. Hardening cycle - preheat 1100°F for 1 hour in neutral salt bath, transfer to 1950°F to stabilize temperature, transfer to 1950°F neutral salt bath, austenitize for 1/2 hour, quench in 1000°F neutral bath and air cool to room temperature.

3. Tempering cycle - hold for 5 hours at 1150°F in neutral salt bath, air cool to room temperature, retemper for 5 hours at 1150°F in neutral salt bath, air cool to room temperature.

All dies were in the hardness range of Rockwell C-52 to C-54.

Table IV

Hot Hardness of Candidate Die Materials

Alloy	Type	AISI Designation	Room Temp. Hardness, Rc	Brinnel Hot Hardness 1100°F	1200°F
FerroTic (HT6)	TiC in Ni-base matrix		56	444	401
Mod 1900	Ni-base		39	363	363
Latrobe	W (very high W)	H-26	54	401	352
Crucible	"	H-26*	53	388	341
Special W	W (hot work tool steel)	H-21	48	352	311
FerroTic (CM)	TiC in high Cr tool steel		70	477	285
W-99	W (hot work tool steel)	H-21	47	331	285
Calmax	Cr-W-Co	-	49	331	269
Tropic AZ	W (hot work tool steel)	H-21	45	285	255
Haynes 6B	Co-base		38	235	217
Tropic AZN	W (hot work	H-21*	40.5	229	187

3.0 AUXILIARY TOOLING DESIGN, FABRICATION AND DEVELOPMENT

The approach to fabricating the tooling and proving its utility was based on prior TRW experience in gear forging development. The early gear tooling development served as a guide and source for "feed back" of information for the later development of the pinion tooling.

Process layouts for forging both the spiral bevel gear, Figure 7, and spiral bevel pinion, Figure 10, were developed so as to use a billet diameter common to both members and to standardize the fixturing and certain tooling components.

3.1 EDM Electrode Design and Fabrication

Two sets of gear die electrodes were fabricated for electrical discharge machining of the die cavities. One was used for the cavitation of the hot coining die the other was used for the cavitation of the cold coining die and a female master reference gage.

The hot coining tooling is designed to account for shrinkage of the forging when it is cooled to room temperature. Data on alloys closely approximating the chemistry of AMS 6265 steel indicate a coefficient of contraction of about 6.7×10^{-6} inches per inch per degree fahrenheit. The expected differences between 1900°F finish forging temperature, 400°F die temperature and room temperature is about 2240°F. This indicates a theoretical shrinkage of .0135 inch per inch from $(1900° + 400° - 70) \times 6.7 \times 10^{-6} \times 9''$ diameter. Other factors which were considered were .001" overburn in cavitating the die, as well as the gear tooth finishing stock allowance of .006"-.010" per surface.

The processes specified that the steady state die temperature during the forging run would be approximately 400°F. The roughing electrode tooth form was sized to allow for .015" overburn per side. The finishing electrode overburn, using a direct current setting of 4-5 amperes, is .001" per surface. The planned process specified a minimum stock allowance of .007 inch per tooth surface and an optimum as close to that value as possible. Any appreciable increase in stock allowance will result in a corresponding increase in grinding time and cost. A decrease in finish stock allowance will require closer control of all machining operations which must be held relative to the gear teeth to assure satisfactory clean up of all gear tooth surfaces at the time of final grinding (4).

The shrinkage allowance of .0135 inch per inch was applied to all linear dimensions of the gear electrode. Angular dimensions were left unchanged. The effect of thermal distortions on the angular dimensions of the gear were determined by measurements taken on the forging, as described in the Appendix, and by observation of the finish grinding in feed and initial contact pattern on the hardened gear. It was found that the "unwinding" normally taking place when cut gears are heat treated, did not occur with the forged tooth gear. This compensation had to be adjusted accordingly on the second development forging cycle.

Several electrode materials were considered for this application. Prior experience had been limited to brass electrodes for gear die applications and has been found to produce a superior surface finish on EDM cavities. However, the wear ratio is about one to one. For through openings and spur gear dies this does not present a particular problem if the electrodes can be made long enough to fully penetrate the work material. For blind end cavities and bevel gear dies a high wear rate is unsatisfactory because it results in loss of fidelity before the electrode reaches the bottom of the cavity with very little remedy other than to use a large number of electrodes in sequence. This in itself presents the additional problem of maintaining an accurate index from one electrode to the next.

Carbon electrodes have a more favorable wear ratio. The ratio is about 1 to 3 compared to 1 to 1 for brass. However, the quality of surface finish obtainable in the die is not as good with carbon electrodes as it is with brass. Carbon is also quite fragile and the cost of carbon electrodes is about 50 percent greater than brass electrodes, although based on the quantity of die material removed per electrode and the rate of metal removal, the carbon electrodes prove to be more economical by a significant margin. They are also relatively light weight and are much easier to handle during the EDM process. Because of the light weight and lower inertia forces encountered, the dithering response of the EDM equipment is better with the carbon electrodes. Both carbon and brass electrodes, Figure 13, were used in the cavitation of the gear forging dies. A set of three carbon electrodes and ten brass electrodes were cut. The carbon electrodes were used for rough cutting and the brass electrodes for finishing. If a rougher surface finish were acceptable, carbon electrodes could have been used for both the roughing and finishing operations with a significant reduction in cavitation time. The need for a good surface finish in the forging die cavity has been established during the course of the program.

After observing the practical wear rates on the electrodes, and the fidelity of the resulting cavity, an optimized utilization schedule was developed. Assuming that die wear and usage required a number of resinks, the need for newly cut electrodes can be reduced to one finisher and one rougher per resunk cavity, as shown in Table V.

3.2 EDM Fixture Design

A fixture was specially designed for use in fabricating the gear and pinion forging dies, using an electrical discharge machining method. The fixture has a self contained lead control cam and follower, and a fully supported rotating arbor which makes it suitable for use on any type of electrical discharge machine as long as the height under the machine ram is adequate for the travel required (Figure 14). The electrode holding arbor has a timing pin

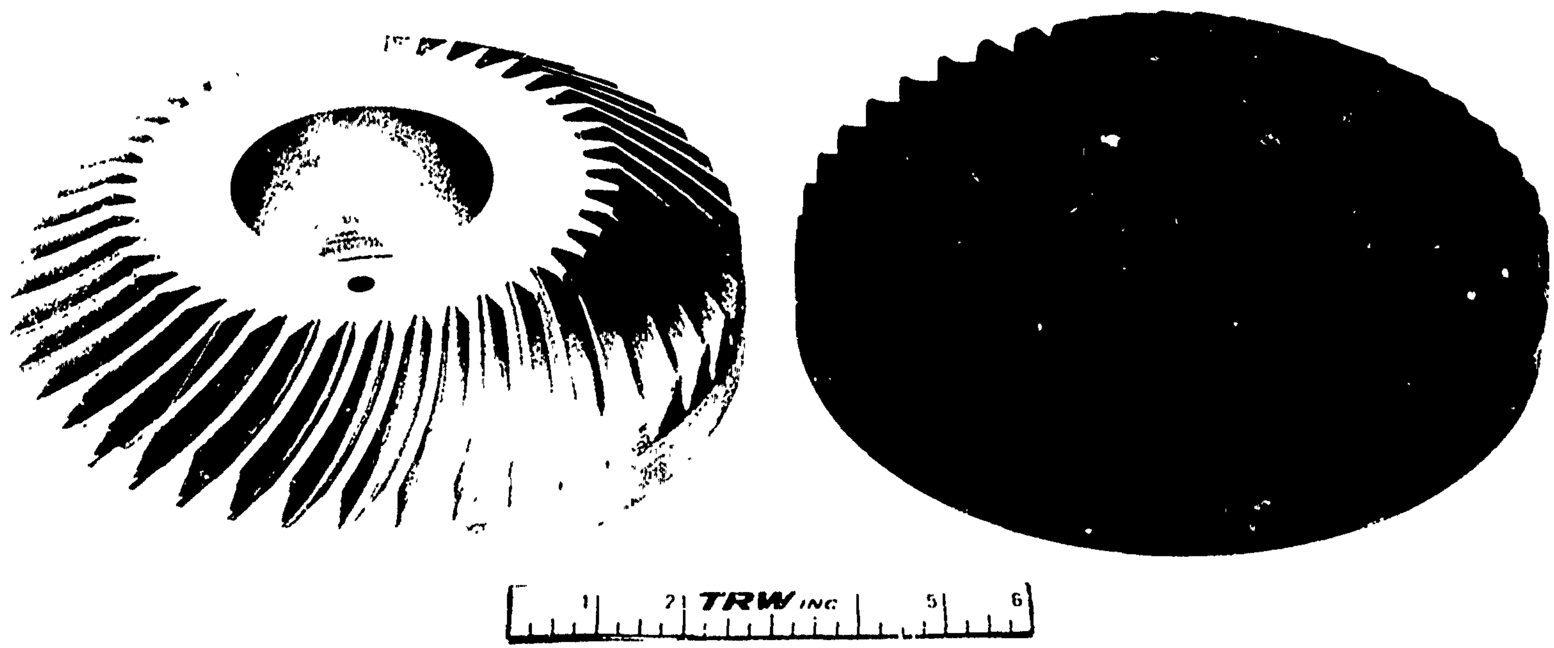


Figure 13. Carbon and brass EDM electrodes.

Table V

Rough (R) and Finish (F) EDM Electrode Utilization Schedule

Electrode Number Into Operation	Die and Electrode Sequence Used	Electrode Number Withdrawn for Recutting
	Original Cavity	
1R, 2R, 3R	1R, 2R, 3R	1R, 2R, 1F
1F, 2F, 3F	1F, 2F, 3F	
	1st Resink	
4R	3R, 4R	3R, 2F
4F	2F, 3F, 4F	
	2nd Resink	
5R	4R, 5R	4R
5F	3F, 4F, 5F	3F
	3rd Resink	
6R	5R, 6R	5R
6F	4F, 5F, 6F	4F
	4th Resink	
7R	6R, 7R	6R
7F	5F, 6F, 7F	5F

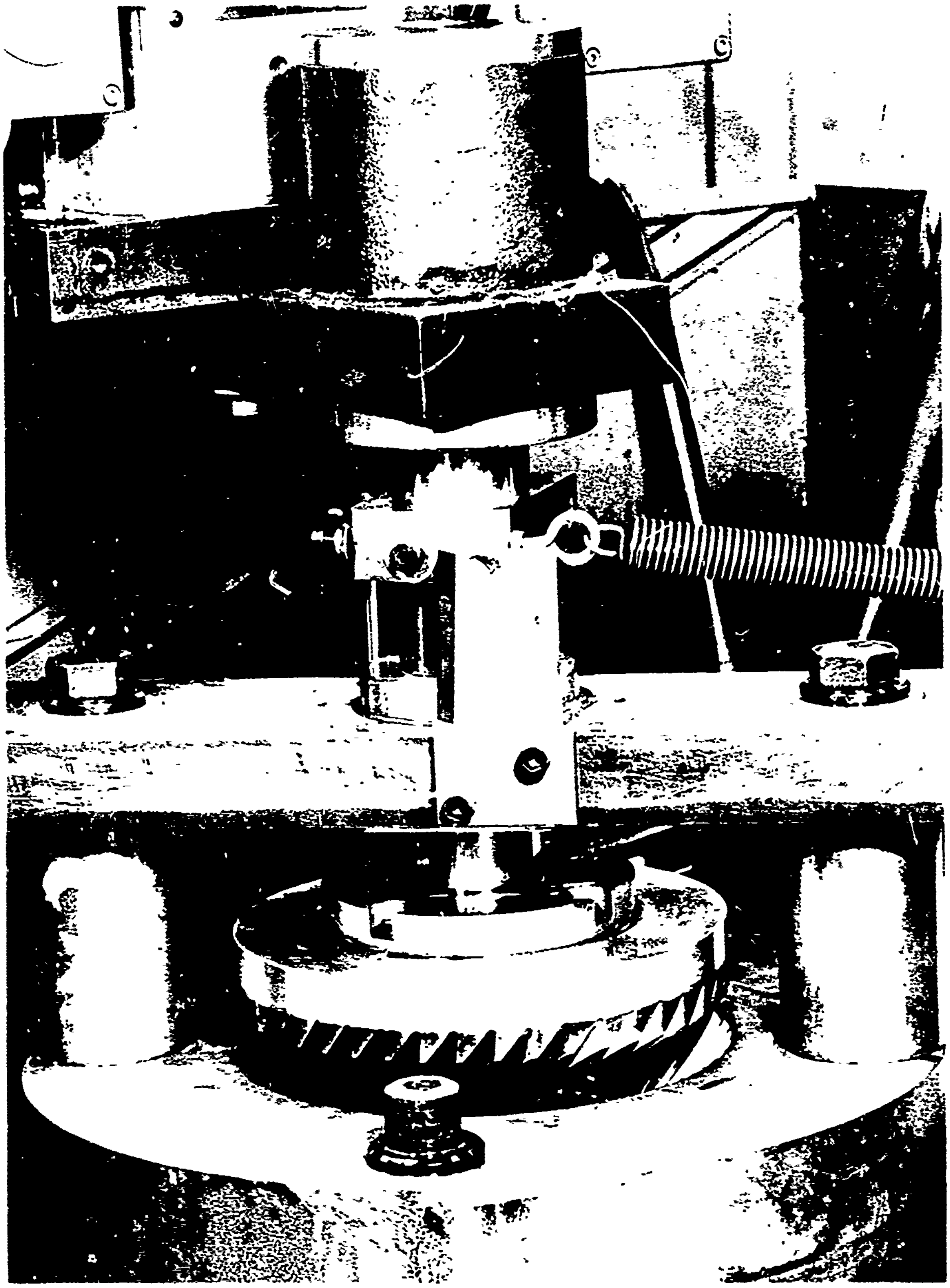


Figure 14. Illustration of EDM Fixture Setup.

to engage the timing hole in the electrodes. The location of these features, in relation to the mounting centerline and tooth elements, is critical in EDM cavitation of the dies. This relationship is established in the mounting of the electrode blanks for generating the teeth on the Gleason gear generator. Accurate positioning of the electrodes is necessary for matching the male and female forms as the cavitation process continues with the mounting of new electrodes in the fixture.

Due to the combination of geometric factors such as pitch, cone angle, spiral angle and depth of gear tooth, there is a negative draft angle in the axial direction on a portion of the tooth of both the gear and the pinion. However, the draft angle is not negative in the direction of rotation along the spiral angle. This feature was investigated since it could have an adverse effect on both the ejection of the forging and cavitation of the forging die by standard EDM techniques. A soft metal matrix was cast around the spiral bevel gear model as an aid in determining the amount of rotation necessary during the axial withdrawal of the gear from the die. By this means, the upper and lower limits for a lead cam were also determined. The axial back taper was also confirmed by measurements taken on a Moore Coordinate measuring machine. An axial back off of approximately .023 inch was observed at the heel end of the gear teeth and .108 inch on the pinion.

Since the gear and pinion mate together, one has a right hand spiral while the other has a left hand spiral and correspondingly the tooth curvature and axial undercuts are in opposite directions. In sinking the cavity, the feed direction of the electrodes must be in opposite directions for the gear and pinion. During the cavitation of the gear forging die the fixture was employed to facilitate maintaining the proper relationship between the electrode and the die, Figure 14. A free rotating spindle supported by anti friction tapered roller bearings is a principal element in the design. This spindle design permits the electrode to rotate at a rate corresponding to the lead direction at any given axial position of the spindle. The lead angle is controlled by an adjustable cam plate which is incorporated in the fixture, thus making the device semi-universal. This makes it suitable for following a helical or spiral motion with any type of electrical discharge machine. The spiral motion is accurately controlled both during the dithering stroke and as the electrode is progressively advanced to full depth.

A refinement was made in the final development cycle for the determination of the optimum cam angle for the control of the EDM electrode. The objective of this optimization is to position the electrode form accurately and symmetrically as it rotates into the die cavity. This positioning insures that the whole form of the electrode is symmetrical with the desired final shape, and the cutting action of the EDM process is uniform over the whole form. The lead angle is controlled by a cam in the EDM fixture. The cam is shown in the center foreground of Figure 14. The 6° angle on the cam used for the first three forge development cycles was the minimum angle defined by the convex side of the gear tooth at the toe. This resulted in unsymmetrical cutting action over the whole tooth forms and probable distortion of the final form.

The lead angle for the cam used in the final development angle was determined by first making a cast of the electrode. The case was mounted on the table of a vertical spindle milling machine, as shown in Figures 15 and 16. The electrode was fully engaged in the cavity of the cast and attached to the machine spindle through a special adaptor.

The mean lead angle was determined from the data shown in Table VI. As the electrode was withdrawn from the cast, it engaged the convex side of the tooth in the cast and was rotated. A backlash or spacing difference between the teeth in the horizontal direction is measured by the dial indicator The backlash noted is the result of tooth profile and tooth taper from heel to toe. The backlash was recorded in the second and third columns of Table VI. These rotational movements in the electrode, limited by the cast surfaces, were noted at measured axial distances from the bottom position. A mean lead angle of 11°-50' was calculated from the data.

A new cam was made and mounted on the EDM fixture. The EDM process was closely specified and monitored, especially the setting up. The necessary steps in the set-up are:

1. Engage the finishing electrode in the existing die cavity.

2. Place the die and electrode assembly in the machine, positioning the die so that the arbor engages the electrode locators freely. Clamp the die to the machine table.

3. Position the cam so that at least the final .125" vertical downward travel is controlled.

4. Raise the electrode free of the die. Replace the finishing electrode with the roughing electrode.

5. Set the gap and proceed with machining.

A sample EDM process control data sheet is shown in Table VII. Only .079" advance of the new EDM electrode form was required to sink the fourth development configuration in the die cavity. This is less than one-half of the former amounts and results in corresponding savings in machine time and die material for resinking. The resinking corrected the geometry and eliminated the die wear from the production run.

3.3 Forging Die Instrumentation

Successful precision forging of complex shapes is the product of good tool design, accurate fabrication of the tools, and close control of the forging process. It was considered important in this case to know what the forging forces were while controlling other parameters such as ram speed, lubrication, tool temperature and work temperature.

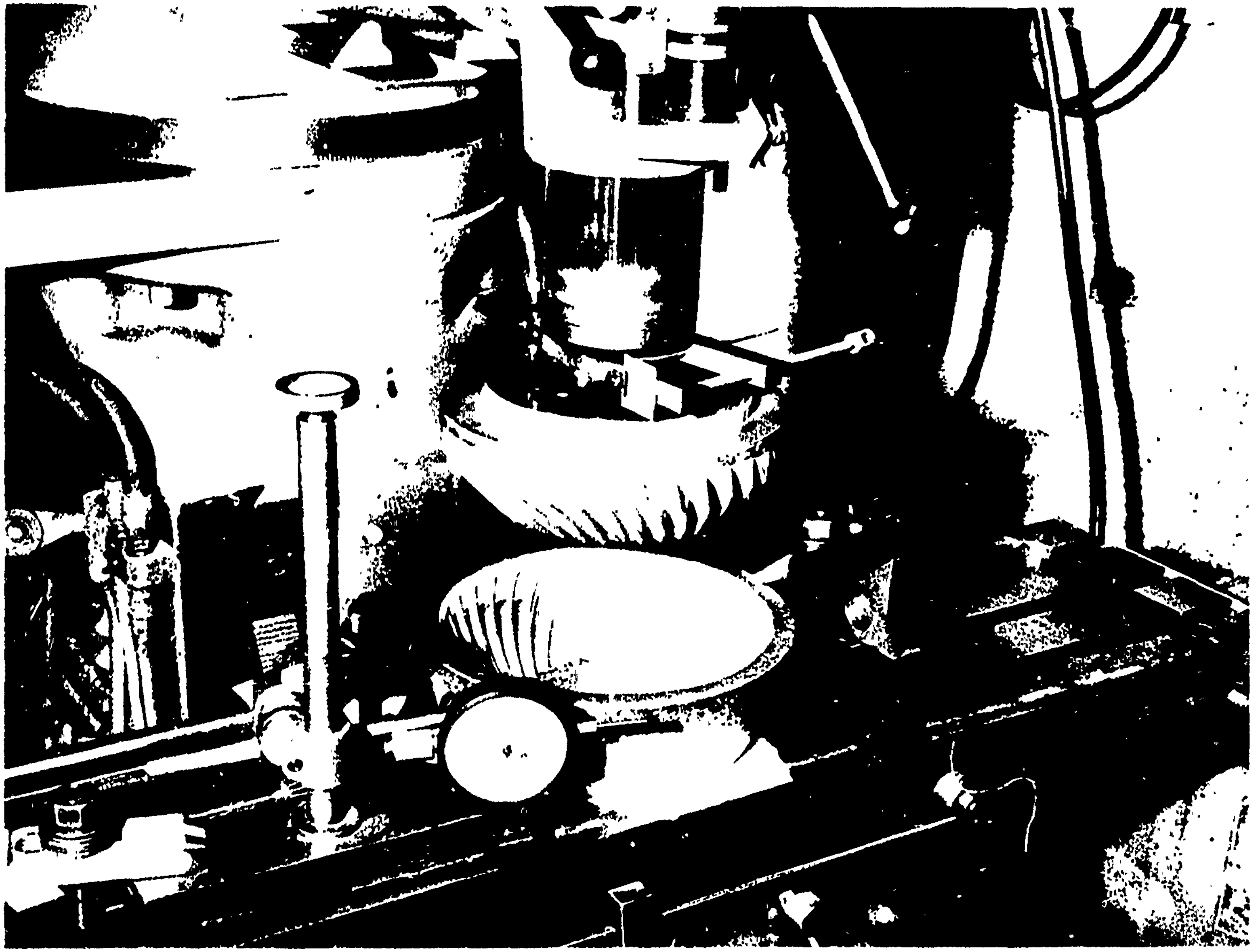


Figure 15. Cast and EDM electrode set-up for determining the mean lead angle.

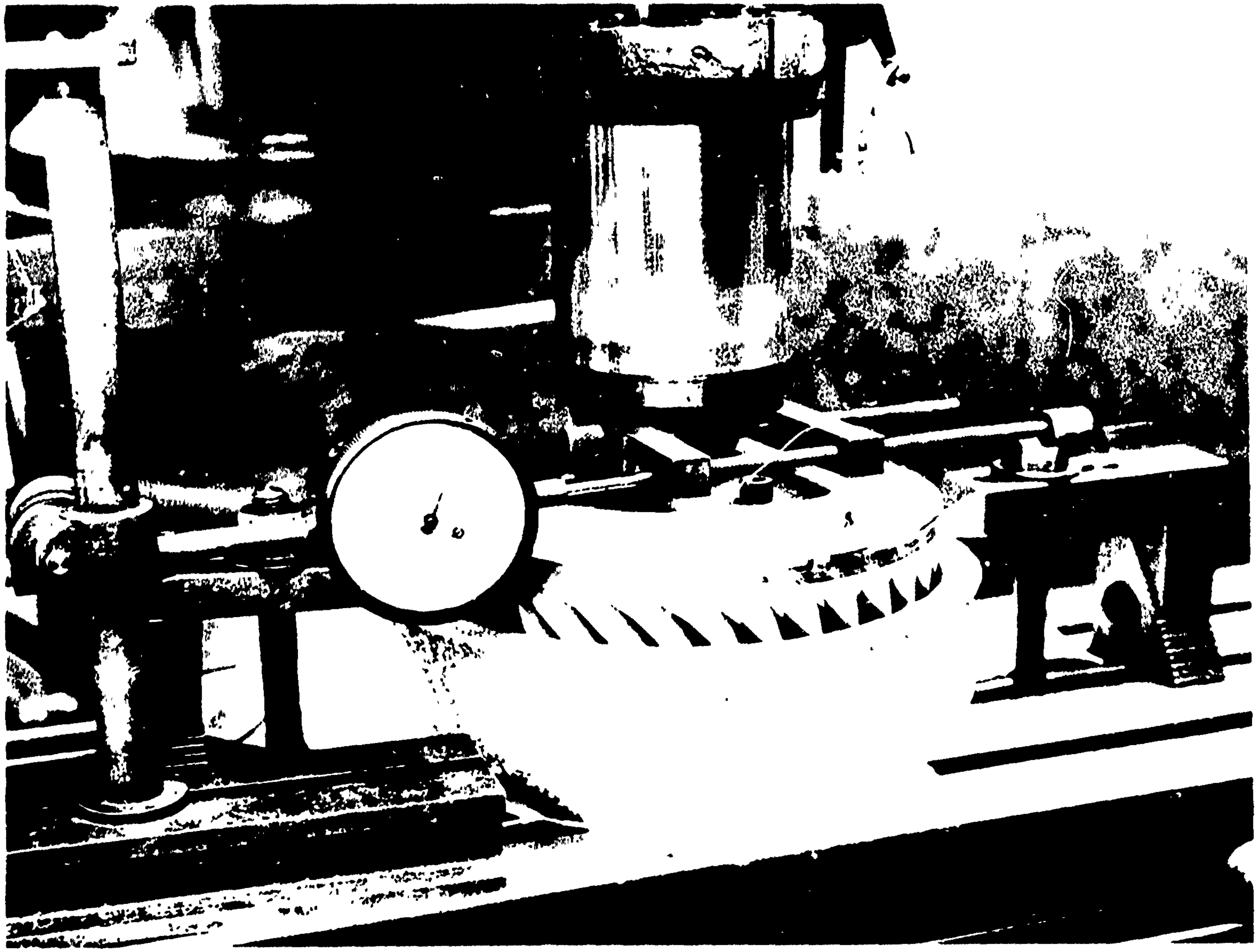


Figure 16. Checking the gear electrode mean lead angle.

Table VI

Fourth Development Gear Lead Angle EDM Cam Data at 2.500 Radius

Vertical Position	Rotation to Convex Side	Rotation to Concave Side	1/2 Difference	Δ Plus "B"	Tangent of Angle
.000	.000	.000			
.002	+.002	-.007	.0045	-.0025	
.005	+.004	-.007	.0055	-.0015	
.010	+.002	-.007	.0045	-.0025	
.015	+.002	-.009	.0055	-.0035	
.020	+.001	-.011	.006	-.005	
.025	+.001	-.013	.007	-.006	.2000
.030	+.001	-.015	.008	-.007	.2000
.035	+.001	-.017	.009	-.008	.2000
.045	+.001	-.021	.011	-.010	.2000
.055	+.001	-.025	.013	-.012	.2000
.065	+.001	-.028	.0145	-.0145	.2080
.075	-.001	-.031	.015	-.016	.2135
.100	-.002	-.041	.0195	-.0215	.215
.125	-.003	-.051	.024	-.027	.216
.150	-.003	-.061	.029	-.031	.2065
.175	-.005	-.071	.033	-.038	.217
.200	-.005	-.081	.038	-.043	.215

Calculated mean lead angle 11° 50'

Table VII

EDM Process Control Data

Type of Machine and Power: Elox HRP 103
NPS D60

EDM Fluid Used (Dielectric Fluid): Texaco 499

Dace Started: February 1, 1971

Date Finished: February 3, 1971

X Pinion Punch Die (check one) BF13773 Rev. A, Det. 23A to 23B, 3rd Development
Gear Punch Die

Electrode Serial No.	Height "A" Dimension (per drawing) Start	Finish	Cutting Actual Time	Volts	Amps MFD	Freq.	Pressure	Suction	Remarks
P1-8S-3 Carbon	2.007	2.029	24 hours 45 minutes	70	10/10	4		9 psi	.370 -.342 = .028 Metal removal including high spots
P2-8S-3 Carbon	2.029	2.039	2 hours 45 minutes	68	5/5	4		9 psi	.342 -.332 = .010 Metal removal
P1-BS-3 Brass	2.039	2.043	3 hours 45 minutes	73	10/2.5	6		9 psi	.332 -.328 = .004 Metal removal
P2-BS-3 Brass	2.034	2.047	4 hours 45 minutes	72	5/1.25	6		10 psi	.328 -.324 = .004

The dies were designed with provisions for load cell and thermocouple inserts. A convenient die heating system and a die lubricating system were installed on the forging press. The gas burner head for die heating was specially designed to conform to the size and shape of the forging dies and provide a uniform and symmetrically applied source of heat.

The total load required to forge a part depends mainly upon the flow stress of the material and the total projected area of the part. Other factors are complex work geometry and flash patterns that highly constrain the flow of the metal in the die. With the tooling designed for this particular application, peak load will occur at the bottom of the stroke during the coining operation. A dynamic load transducer was incorporated in the design of the coining die retainer to monitor the loads experienced during the development of the billet volume. The unit is fitted with a pair of redundant full bridge circuits. Each bridge is composed of four active strain gates and four temperature compensating elements. The transducer is designed to handle a total load up to six million pounds (3000 tons). A strain versus load calibration was made and linearity was verified over twenty percent of the load range. The load cell design and circuity is illustrated in Figure 17. The instrument read-out consoles are shown in operation in Figure 18.

3.4 EDM Machining of the Dies

Electrical discharge machining (EDM) was the method selected to form the forging die cavities carrying the finished tooth forms. This is the only feasible process capable of producing the required detail in the die cavity and yielding the desired dimensional tolerances at an acceptable cost. However, the fundamental nature of the EDM process is such that certain metallurgical characteristics that are generated on the die surfaces must be recognized and considered in the overall evaluation of the gear forging process. The development of a special EDM procedure for the gear forging dies on this program was beyond the scope of the contract. However, it was possible to specify some of the process conditions and evaluate the end results in order to improve die performance.

The hot coining dies were cavitated on the Elox HRP 104 machine, while the cold coining die was sunk on a Easco Sparkatron Model ES162. Both machines were equipped with a dual power supply with a maximum current rating of 120 amperes. However, the maximum current drawn during the roughing cut was limited to 30 amperes on each machine to avoid the overburn problem. The machines have slightly different power characteristics but produce essentially the same results. The Elox HRP 104 is a constant total current machine while the Sparkatron machine produces a constant current density on the work. This latter feature produces a nearly constant cutting rate as the electrode is engaged to an increasing depth and also minimizes the chance of arcing during first contact. There was no noticeable difference in the surface finish on the die. By visual comparison with roughness standards the surface finish was estimated to be 60 rms or better.

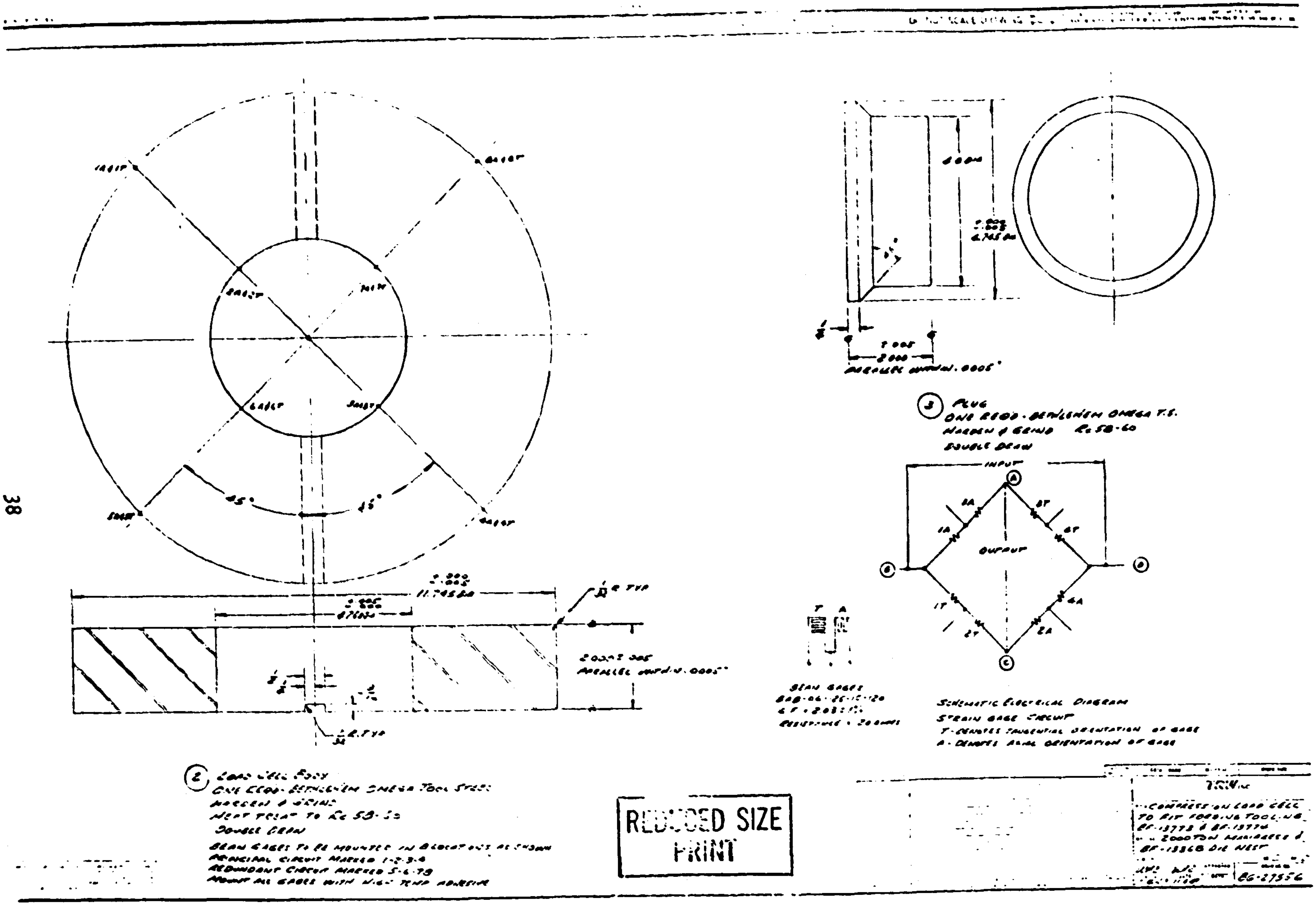


Figure 17 Forging die load cell circuit diagram.

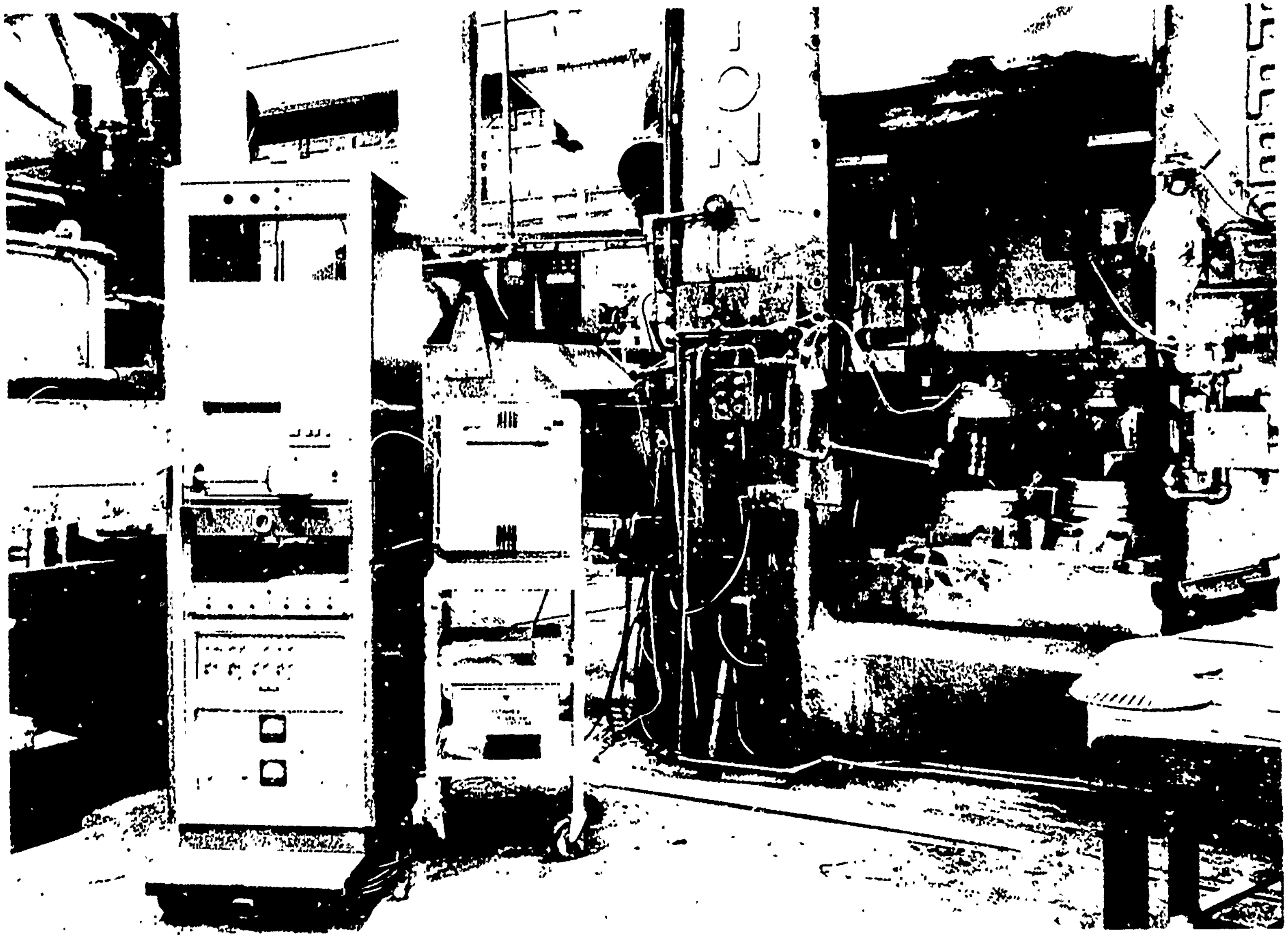


Figure 18. Die Temperature and Forging Force Instrumentation.

A problem which was encountered related to the difficulty of recirculating the EDM dielectric in a blind cavity. A free cutting condition prevailed until the electrode penetrated to a depth where the flow of electrolyte through the gear tooth spaces began to be throttled off. Flushing holes could not readily be drilled in the electrode because of the complicated geometry of the spiral teeth. In any case, an imperfection in the cavity would result from the use of conventional flushing holes. To eliminate the spikes left by the flushing holes would have required some manual finishing. This problem was avoided by making minor modifications of the electrode design so that circulation of the electrolyte was maintained regardless of the depth of penetration into the workpiece, and a suction at the bottom of the cavity, through the center hole in the die, was applied.

The unique surface conditions resulting from EDM are: (1) a recast layer that can be controlled for depth but cannot be eliminated except by chemical or mechanical processes and (2) a surface profile formed by contiguous craters that is not comparable to the identical rms value for a striated surface.

The EDM parameters for roughing and finishing were established to insure that the degraded surface material generated in the roughing operation was removed and the recast layer formed in the finishing was in the range of .0005 to .0015 inch. The EDM roughing cycle was performed in approximately 24 hours at 16 kc/sec. starting at 20 amps. Finishing was completed in about 12 hours at 65 kc/sec. and 4 amps. The penetration allowance for finishing was .025 inch. This surface was then abrasive blasted to further smooth the surface and remove approximately .0001-0003 inch. The resulting rms surface finish was approximately 50.

The typical 16-32 rms surface finish on a precision forging die is generally developed by hand polishing. This is an impractical approach for the gear form cavity. The smoothened surface finish tends to reduce friction and leave a better finish on the forging. However, in this case, neither the surface finish nor the surface friction were observed to be a problem. The minute and uniform crater left by the specified EDM process appears to retain the die lube and this compensates for the slightly rougher surface.

4.0 DEVELOPMENT PHASE

After fabrication of the basic preforming and hot coining tooling and installation of the tooling in the press was completed, Figure 19, a standard tryout procedure was followed to establish the forging process parameters.

4.1 Gear Forging Development

A series of short billets of SAE 1020 steel were used to first verify the metal flow in the preform die. The closed height of the preform die was adjusted by shimming until the predetermined web thicknesses were obtained. Then volume was added to the billet incrementally to achieve more complete fill. At this stage, the forgings were also struck in the hot coining station to evaluate the capability of the tooling to produce the final configuration. Several minor modifications and height adjustments were necessary to achieve a satisfactory balance in the material displacement at the preforming and coining stations. Records were made of process parameters such as billet temperature, heating time, billet length, load, transfer, and unload procedure, lube procedure and cycle time that would later form a standard operating procedure to assure repeatability in the quality of the forgings. The billets were heated in a rotating electric furnace with an Exogas atmosphere control and gas curtain. This did not prove to be entirely satisfactory due, in part at least, to the large open volume of the furnace when charged with only a few pieces. As a matter of expediency the billets were containerized to further limit atmospheric contact. This procedure was found to be quite effective providing that all forging was accomplished in a single heating. To assure the existence of sufficient residual heat for the coining operation and to provide the operator with a slight time "cushion" in transferring the forging from "preform" to "coin" the billet temperature was 2050°F. Due to the weight and configuration of the preform a certain amount of experience and dexterity is required in the transfer of the forging. For greatest dimensional repeatability of the forgings, the time lapse between the removal of the billet from the furnace and the time of impact at the coining station should be as uniform as possible. The forging cycle time for the gear averaged less than 30 seconds, furnace to floor time and was consistent enough to achieve the desired results.

A better control would be to monitor the billet temperature throughout the forging cycle with a variable delay just prior to the coining blow. The coining blow could be triggered just as the billet reaches some predetermined temperature. Fortunately, however, the success of the process does not depend upon achieving control of the forging parameters to quite this degree.

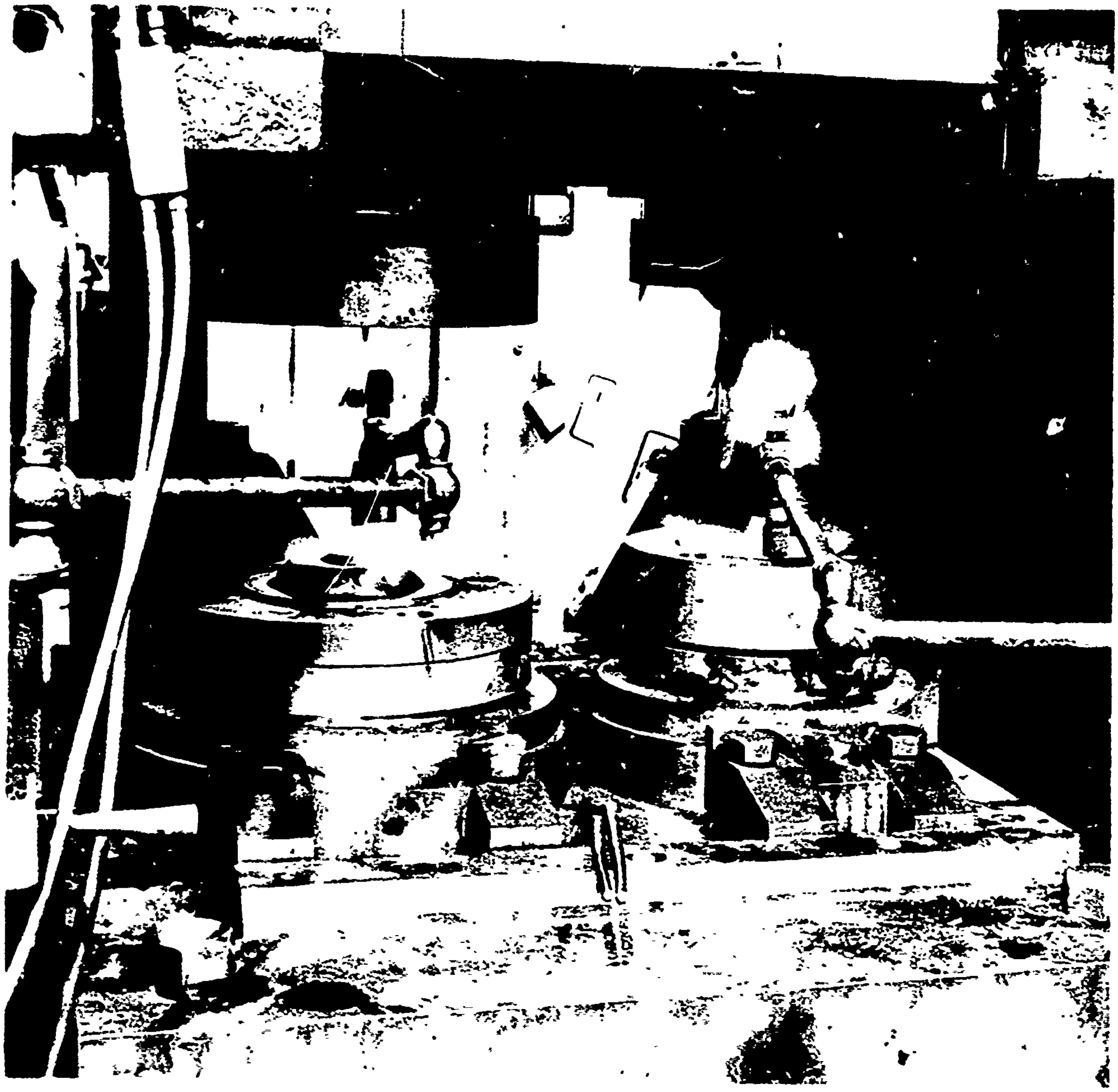


Figure 19. Gear forging tooling installed in press.

During the tooling tryout, a five percent (solid) aqueous graphite die lube was used for both the preform and hot coin dies. The spray time was approximately five seconds per station. This application of lube appears to be satisfactory since sticking did not occur and excess lube build up in the dies was not observed. Both upper and lower die members were lubricated simultaneously by using a "T" connector on a manual lube gun. The dies, Figure 19, were heated for about 45 minutes with a gas torch at the hot coin station to avoid direct impingement of the flame on the critical surfaces of the die. Both the pneumatic ejector at the preform station and the spring shedders at the coining station functioned normally during the die tryout run. Finish forgings were freed from the die and lifted one to two inches before being shed from the punch. From this height they dropped back onto the lower die plate where they were supported by the lower ejector pin until removed by the press operator. No damage to either workpiece or tooling was observed or was anticipated as a result of this procedure. Figure 20 illustrates the relative work performed at each forging station.

Defects were observed in two areas on the first development cycle hot coined forgings. A peripheral flaw resembling a lap or indentation appeared on the tips of the teeth near the small end of the gear forging. The flaw occurred in a circular pattern. Some teeth which did not exhibit this flaw were located adjacent to the point on the forging where the greatest amount of flash occurred, indicating that inadequate die fill was the cause of this defect.

The second visual defect was a slight lack of fill at the large end of the gear teeth. The degree of underfill varied slightly from piece to piece. On the pieces which had an eccentric flash pattern, the lack of fill was greatest on the gear teeth near the point of minimum flash and was minimum in the areas where the greatest amount of flash occurred.

Based on the observed condition of the forging, relative to the presence or absence of flash, it was concluded that at least one, and perhaps both, of the defects would be eliminated by getting better fill and closer conformity to the preform design at the preform station. It followed that to accomplish this, either greater billet volume was required or the dies must be closed more to reduce the flash thickness and force material into the areas not being filled. The latter approach required some reworking of the preform die contour to direct material toward the locations where additional material was required. Both of these approaches imposed an additional energy input requirement. It was observed that practically all of the ram energy of the press was being expended during the preforming operation and the existing press capacity was marginal. This was manifested by the fact that after the preform blow the ram passed through bottom dead center but did not fully return to top center position. As a consequence, to operate the press on the next successive blow it was necessary to "jog" the ram up to its starting position. When either the volume of the preform was increased or the gap on the preform tooling was decreased, greater energy was absorbed by the workpiece and more "jogging" action was required to get the ram back to starting position for the next hit.

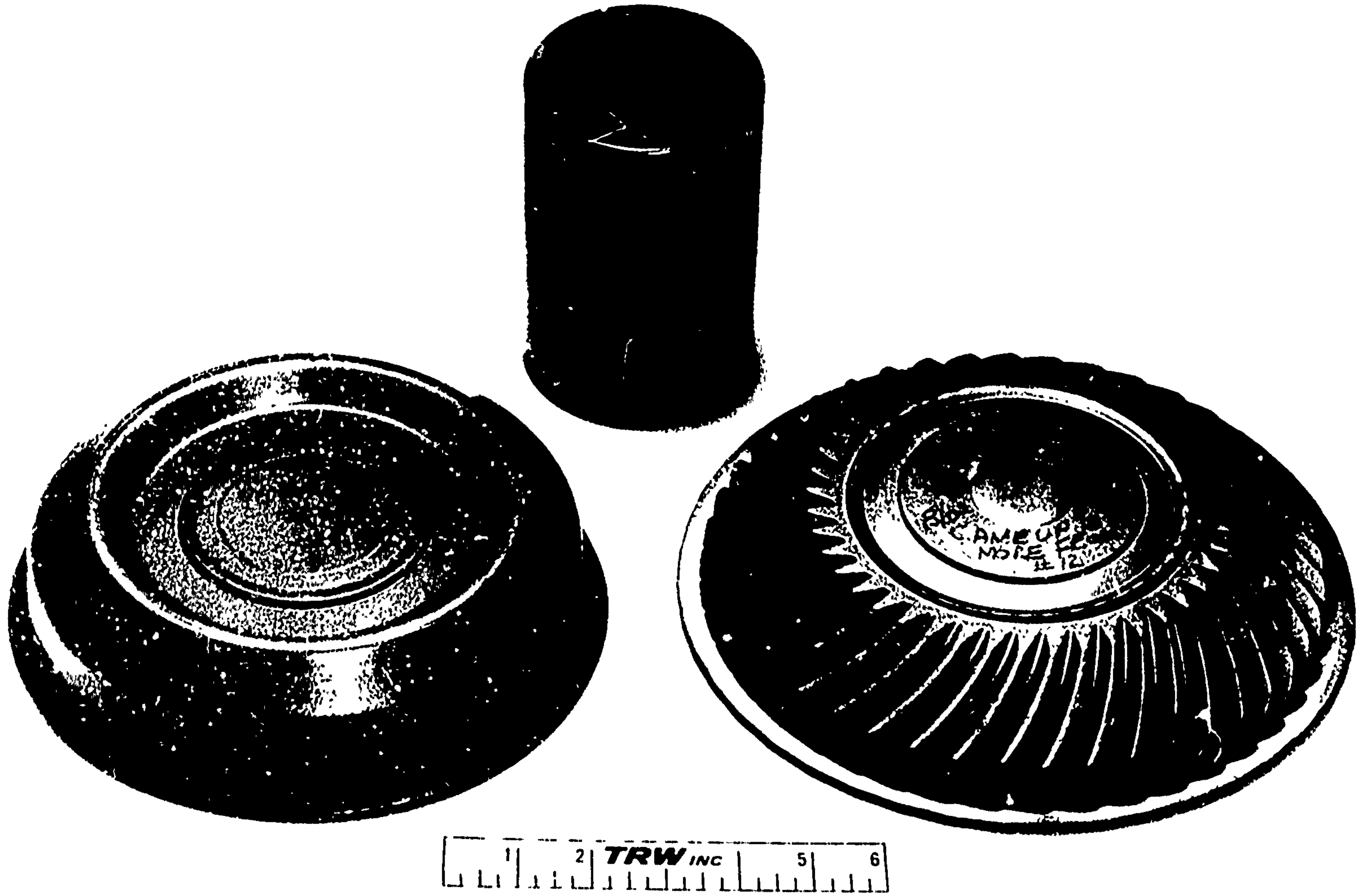


Figure 20. Forged Spiral Bevel Gears.

After considering alternates such as increasing the billet temperature and going to a larger diameter on the billet stock it was decided to increase the energy in the press flywheel. Strain readings taken on the tooling indicated the peak forces developed were less than 2000 tons, ranging between 1650 and 1750 tons. The maximum force exerted during the preforming hit was determined by flywheel velocity decay. It was well below the structural design limits for the press. A modification was designed in the pulley ratios to gain additional flywheel energy. The modification increased the speed of the flywheel from 40 rpm to 80 rpm. This has a very pronounced effect since energy is proportional to the square of the velocity. Thus, as the flywheel speed is doubled from 40 rpm, the energy of the flywheel will quadruple.

One effect of running the press at a higher speed is that the contact time of the die with the hot billet and preform will be proportionately reduced. Reduction of heat loss between hits will allow the workpiece to maintain temperature for the second hit. At the same time the shorter contact time of the die with the hot workpiece material will lessen the tendency of the die to soften and result in greater die life. The displacement velocity of the metal in the forging will also increase proportionally with an increase in ram speed. The side effects associated with an increased displacement velocity may be either beneficial or detrimental. On the other hand, a better fill of corners and grooves can be expected but this could result in an adverse effect on die life.

After considering the various effects that would result from this increase of ram velocity, the press was modified to run at 80 strokes per minute. As predicted, this did provide enough energy for forging a preform without stopping the ram. The press cycle was completed on the preform stroke and the ram returned to the normal starting position in readiness for the next hit. Transfer to the hot coining station was then accomplished without delay and complete filling of the gear form resulted.

Recorded load readings for the hot coining operation ranged from 1310 tons to 1430 tons for the twelve gear forgings produced after the press was modified to run at the higher speed. Typical temperature and force traces are shown in Figure 21.

4.1.1 Cold Coin Corrective Operation

A cold coining operation was included in the initial gear forging processing sequence to provide additional control over size and geometry. In addition to serving as a quality control procedure, the cold coining operation may provide certain economic benefits. The coining operation may be used to regain flatness and to correct warpage and thermal distortions that can occur while cooling after hot coining. There is also the possibility that small inaccuracies produced in the hot coining operation as the die begins to wear may be corrected by cold coining. To the extent that cold coining can provide remedial treatment, the useful life of the

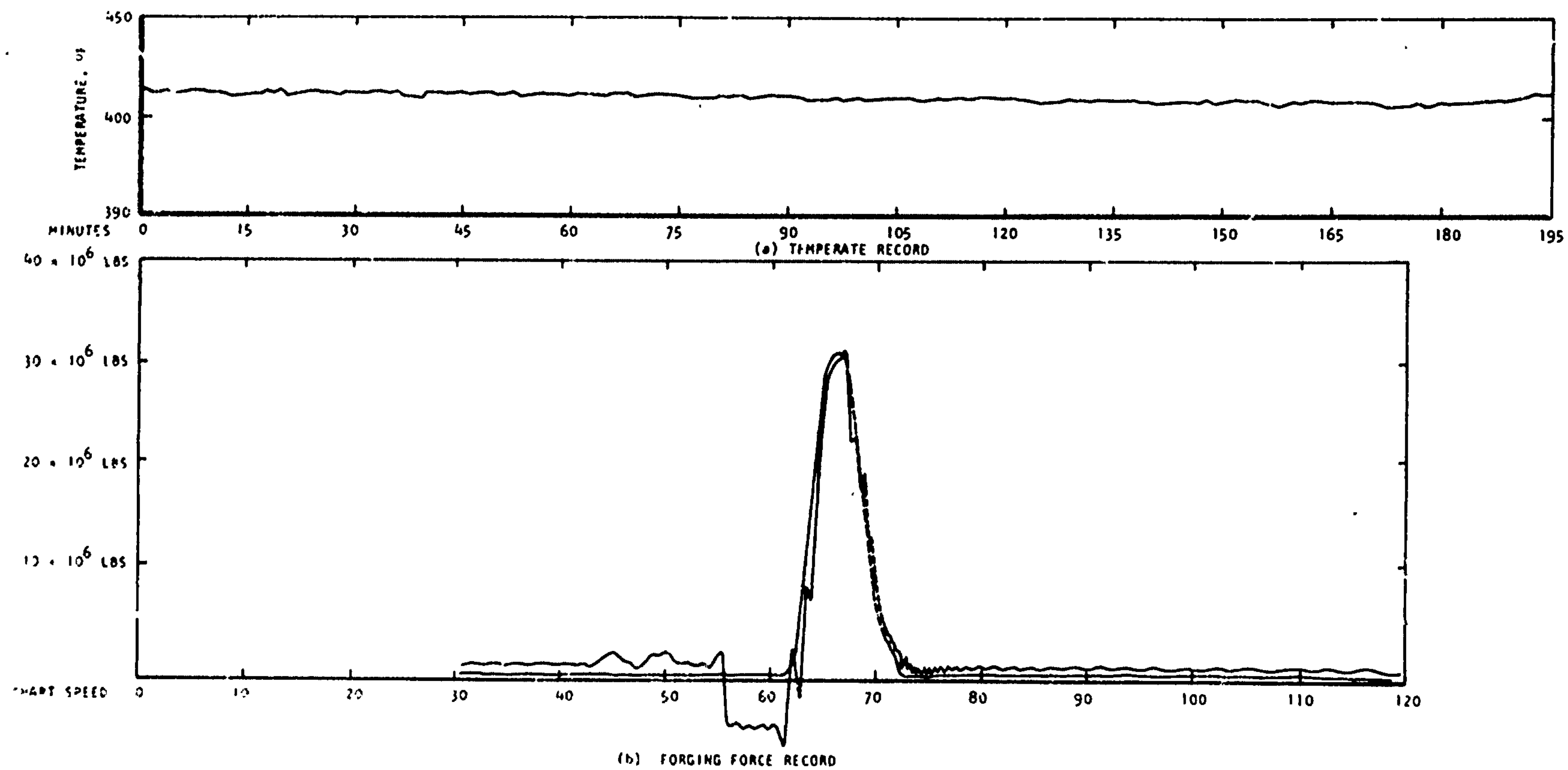


Figure 21. Gear forging die temperature and force recording.

hot coining dies may be extended and this could have a favorable influence on the economics of the process. However, as anticipated, only a small amount of material displacement can be accomplished by cold coining.

The cold coining die, Figure 22, should show very little wear over a large number of coined parts if proper lubrication is maintained between the die and the workpiece. Since no heat is involved for this operation, hot forging die lubricants are not generally suitable. For ease of handling and other economic reasons the lubricant is generally applied to the workpiece instead of the die in the case of cold forging operations. Oils, greases and saponaceous compounds have been found satisfactory for cold metal working operations. For coining operations where high unit pressures accompanied by only a small amount of material displacement are involved, a saponaceous compound is preferred over the greases and oil lubricants. To be most effective these should be applied to a phosphate conversion coat to assure uniform coating and satisfactory retention of the lubricant.

For cold coining the spiral bevel gears, a commercially available stearate was used for the lubricant and this was applied after the parts were chemically cleaned and bonderized with zinc phosphate. The following procedure was used for processing forged gears prior to cold coining:

Operation	Purpose	Method
1. Grit Blast	Remove bulk scale	Tumble blast on rotary table, 320 grit zirconium oxide
2. Pickle	Remove residual scale and surface contaminants	Dilute muriatic acid
3. Water Rinse	Neutralize	Overflowing tank
4. Bonderize	Provide lubricant retention film (zinc phosphate)	Immersion tank (5 minutes)
5. Water Rinse	Remove excess phosphate	Overflowing tank
6. Alkaline Dip	Neutralize phosphate coating	Immersion tank (1 minute)
7. Lube Coat	Provide saponaceous coating	Immersion tank, stearate dip (2 minutes)
8. Dry	Remove surplus liquid	Circulating air

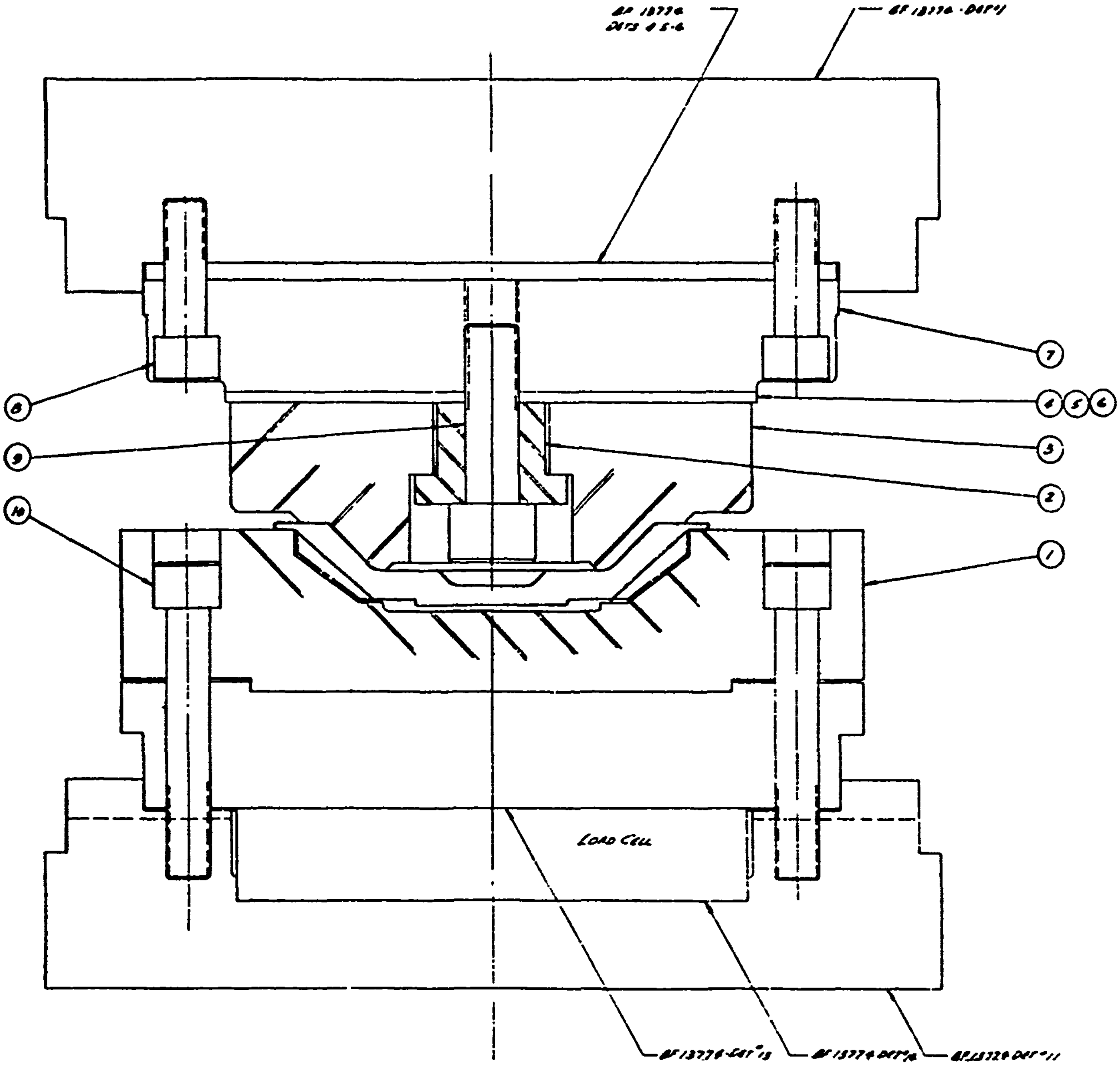


Figure 22. Design layout for gear cold coin tooling.

A minimum amount of handling was done after the parts had been lube coated. After cold coining, the residual lube was stripped by a hot water or steam rinse. The phosphate bond coat was removed by the subsequent machining operations and functioned as a rust inhibitor during the time that the parts are stored prior to machining.

4.1.2 Qualification of First Development Gear Forgings

The first development forged gears were processed through the machining and heat treat operations in order to prove the dimensional quality of the forged tooth profile by observing the degree of clean up in the finish grinding of the teeth.

Because of the complex geometry of spiral bevel gears it is very difficult to establish meaningful dimensional criteria which can be used as an acceptance standard. Spiral bevel gear teeth and spaces are tapered so that tooth thickness can only be related to a theoretical diametral location. In addition, the tooth shape is curved, thus making tooth spacing, pitch and lead difficult to measure. Most spiral bevel gear measurements are stated in terms of specific data point locations relative either to the central axis of the gear, the vertex point or the thrust face of the gear (5).

In the case of a forged gear, the problem is to find a method of identifying these reference surfaces and then being able to position the part to fix the location of these surfaces. Since, initially the forging will not have a hole or central axis location, all other dimensions must be related to the gear tooth profiles. However, the gear teeth are not sized to finished dimensions at this point and so it is necessary to make certain assumptions that compensate for the finishing stock allowance. Then using a properly designed fixture to pick up a location from the gear tooth profiles, the central axis and pitch cone apex can be established. With these references established the secondary reference central bore and back face can be machined in the forging.

A gage that will monitor changes in the gear configuration as the die wears has been designed and fabricated, see Figure 23. The gage has a reverse configuration in the gear and was made to fit a cut master reference gear. Deviations from the standard profile are determined by using feeler gage wires. Although it is difficult to precisely identify specific parameters which cause observed deviations, the gage does determine the total composite error. The type and magnitude of the specific elements in error must be measured for intelligent direction of tooling and process refinements.

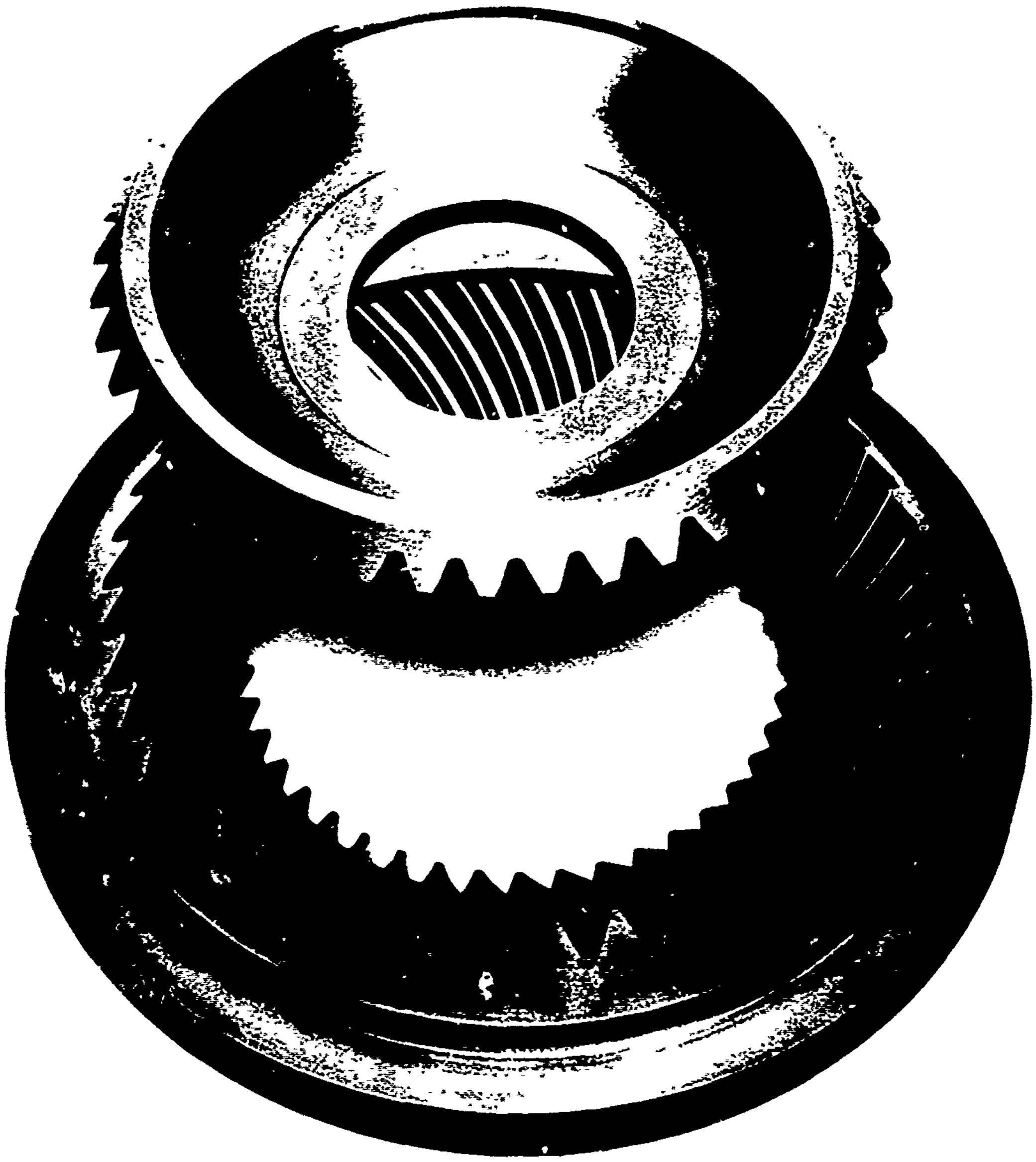


Figure 23. Semi-finished spiral bevel gear model and dimensional reference gage.

The objective for processing and evaluating the first lot of gear forgings was to establish the validity of the assumptions made in regard to forging and tooling distortions resulting from the working temperatures involved. In order to establish finite values, the gear teeth on the forgings were ground to the finished gear dimensions. These forgings were first machined to establish the reference locating surfaces from which the tooth grinding operation is performed. Different methods were used to establish these locating surfaces.

The first method involved locating on three tooth spaces about 120° apart. A uniform excess stock envelop of .007 inch on the teeth was assumed and the reference surface location was calculated in relation to the tooth locators. A locating diameter and face was then machined as calculated. This method resulted in a 90% clean up of the tooth form ground to finish size.

The second method used a deviation averaging approach. The machining of the reference surface was done while nesting the forged gear form in a female replica of the machined gear reference master. The gear forging reference surfaces were machined in a calculated relation to the female receiver. This method resulted in about a 65% clean up of the gear form when ground to size. The distribution of the excess stock along the length of the tooth was more uniform because the spiral angle was averaged by this method. It appeared that a small change in the tooth pressure angle and spiral angles adding stock on the convex side, would give an ideal stock distribution on the forged tooth form.

It is desirable to obtain a gear tooth configuration on the forging which is as close to the finished ground gear geometry as possible. This is important in order to achieve acceptable uniformity of the case depth on the finished product. The permissable variation in case depth is quite small, therefore, there is some advantage in being able to anticipate and precompensate for distortions which might occur during processing.

A significant change in spiral angle is generally experienced during the heat treatment of conventionally generated spiral bevel gears. Whether or not a similar change would occur in the case of the forged tooth gears was not known. The first lot gear forgings were processed through the standard carburizing and heat treating cycle to determine the magnitude of the distortions which can be expected in subsequent lots. The heat treat process steps for the rough cut gear blank are in the following sequence:

1. selective copper plate,

2. carburize at 1700°F 8 hours for .060"-.065" case depth,

3. cool in protective atmosphere,

4. clean and protective copper plate,

5. anneal two hours at 1100°F,

6. clean and copper flash plate,

7. harden, die quench from 1525°F,

8. low temperature transformation, 3 hours at -110°F, and

9. double draw, 2 hours at 300°F.

The forged gears, with a geometry comparable to the cut gear blanks, were found to be more dimensionally stable for the heat treating cycle used. This observation on small lots may not be statistically conclusive but it does tend to indicate that the residual stress state of the forged gear was presumably lower than for the equivalent cut gear.

When compared to cut gears, the gear forgings which had been hot coined only, had conformed better than those which had been both hot and cold coined. A greater deviation was observed in the face cone angle for the cold coined gears. There were indications that during the cold coining operation greater pressure had been exerted at the heel of the gear tooth than at the toe, causing the gear to flatten out slightly. The uneven pressure distribution may have occurred because the gear forging was partially restrained by the flash material during the cold coining operation. Uneven pressure could also be caused by a slight misfit between the coining punch and the gear forging. Both of these conditions could be eliminated. However, the dimensional quality of the hot finished gears was so good that the need for the cold coining corrective operation was questionable. The operation was omitted in the subsequent development cycles.

Table VIII is a tabulation of the measurements taken on this first lot of forged gears. The values shown are direct dial gage readings indicating the differences between the forging and a production cut gear master. The pitch cone reading is taken over balls between the teeth. The ratio between the diametral reading and actual stock on the form of the tooth is 8:3. Based on the data, it was calculated that a 3° decrease in the forged spiral angle would position the .010" stock as required at the concave toe of the tooth form. Directions to incorporate this change in the EDM electrodes for the second gear development cycle were issued.

4.1.3 Die Failure Analysis and Corrective Action

During the forging trials, conducted on the first development cycle for the gear, the original die of H-21 material fractured after about thirty forging blows. The fracture which occurred in the H-21 steel hot coining die is illustrated in Figure 24. The failure can be described as a through fracture running in an essentially radial direction between the outside diameter of the die flange to the central hole. It is clearly evident in Figure 24 that the fracture does not go through a minimum section thickness. The

Table VIII

Gear Stock Distribution - 1st Lot Forgings

		ROOT		PITCH	
		Heel	Toe	Heel	Toe
Gear #1 - Cold Coined	Maximum	+.0105	-.003	+.002	-.004
Ball Located	Minimum	+.0055	-.0065	+.003	-.008
Gear #2 - Cold Coined	Maximum	+.0105	-.0035	+.004	-.004
Ball Located	Minimum	+.004	-.008	+.003	-.010
Gear #3 - As Forged	Maximum	-.003	-.005	+.008	-.007
Nest Located	Minimum	-.0155	-.0105	+.020	+.014
Gear #4 - As Forged	Maximum	-.001	-.0055	+.006	+.006
Nest Located	Minimum	-.0145	-.010	+.019	-.012
Gear #5 - Cold Coined	Maximum	+.0105	-.0035	+.001	-.003
Ball Located	Minimum	+.0035	-.0075	+.004	+.009
Gear #6 - Cold Coined	Maximum	+.010	+.0025	+.003	+.002
Ball Located	Minimum	+.0055	-.001	+.002	-.003
Gear #7 - As Forged	Maximum	.000	-.007	-.005	-.007
Nest Located	Minimum	-.025	-.016	+.0[illegible]8	+.018
Gear #8 - As Forged	Maximum	-.0015	-.004	+.005	+.005
Ball Located	Minimum	-.014	-.010	+.013	+.012
Gear #9 - As Forged	Maximum	-.0055	+.005	-.011	-.008
Ball Located	Minimum	-.0135	+.0105	-.018	+.012

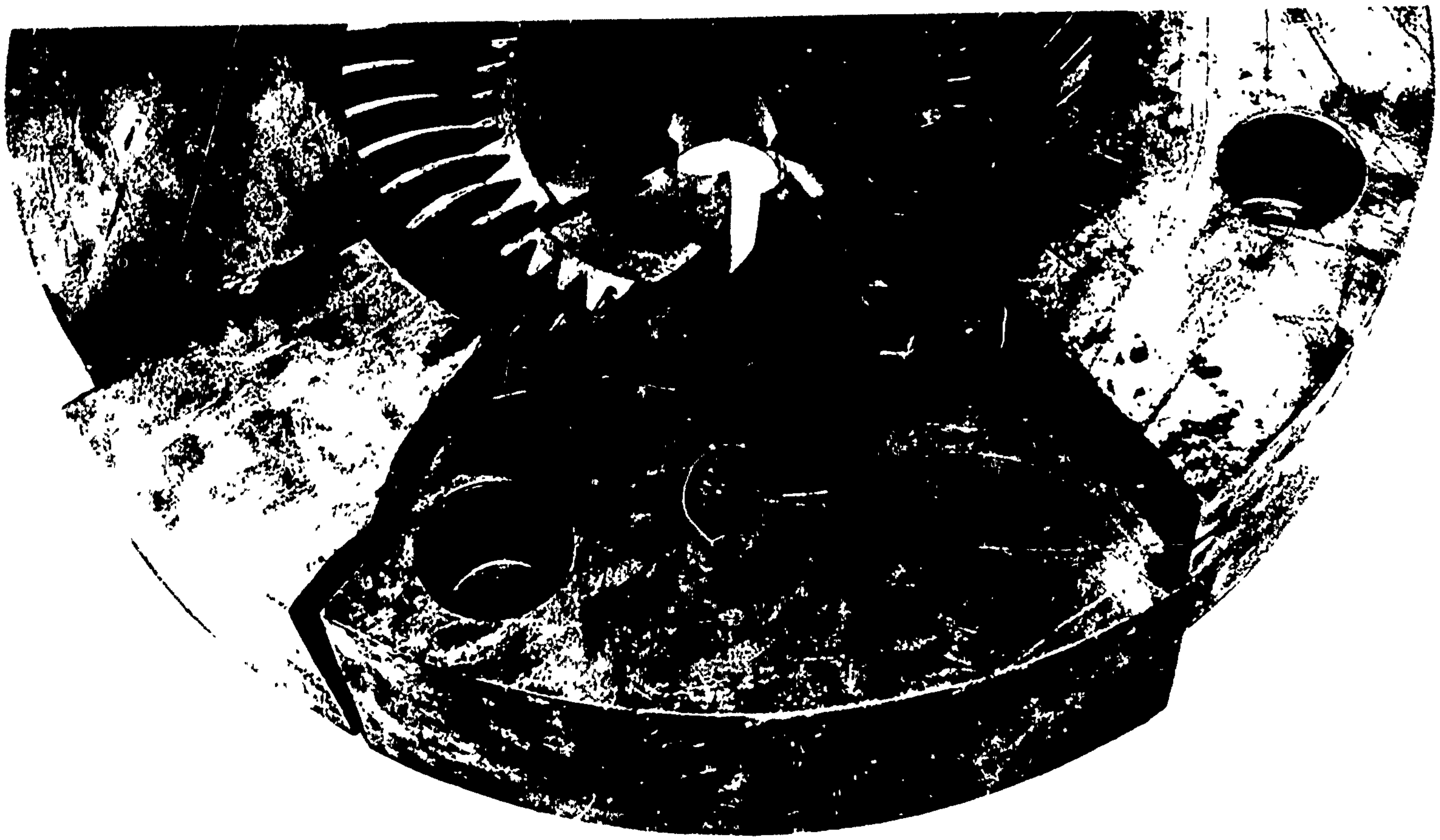


Figure 24. Orientation of fracture in H-21 gear die. Scale - half size.

fracture does not pass through the bolting hole in the flange and it takes a transverse path across the gear tooth configuration rather than following a tooth space as might normally be expected with an impact fracture. Figure 25 shows the unetched adjacent surfaces of the fracture after cleaning. The cleaning was done ultrasonically using a dilute detergent in hot water (130-140°F) followed by rinsing and air drying.

The general appearance of the fracture surfaces indicates an abrupt failure which occurred during a single impact rather than a progressive thermal-mechanical fatigue failure which might occur over a number of succeeding forging blows. The variations in texture of the fracture indicate that the direction of the fracture was from the center outward. This would correspond to the direction of the stress gradient.

Figure 26 shows the unetched fracture surfaces at 2.5X magnification. Minor inclusions which are not regarded as being significant can be seen. There is also a small crack visible in the trough between two gear teeth near the top of Figure 26. The dark zone along the top edge of the central die section was probably caused by extrusion of metal and graphite lube into the fracture as pieces were forged in the die after the breakage. The general direction of the surface texture observed in the fracture surface suggests that the failure initiated near the juncture of the gear tooth section with the flat inner top surface of the cavity and radiated outward from this point. Any bending stress which developed from bolting the die to the holder would have been maximum at this point. The metallurgical examination failed to account for the failure.

In addition to the physical examination of the failed die as described in this section of the report, a stress analysis was made to study the effect of the combined loads imposed upon the die. The input parameters were transposed into ELAS format for computer analysis. ELAS is a finite element, general purpose computer program for equilibrium problems of linear structures. The programming and analysis procedure is described in NASA (Jet Propulsion Lab.) Technical Report 32-1240 (6). In the ELAS program, solutions are obtained by means of the displacement method and the finite element technique. The stresses are provided by the best-fit strain tensors in the least-squares sense at the mesh points.

Figure 27 illustrates how the die was divided up into triangular and quadrilateral toroidal elements. The gear teeth were simplified to a conical surface at the back cone distance. The forging load was estimated at 3,000,000 pounds. This axial load was applied to the projected area of the active faces of the die and assumed to act hydrostatically during forging. The resultant pressure load was calculated to be 68,300 psi. The surfaces on which the pressure load was assumed to act are shown in Figure 27. Also shown are the reaction locations. The inner two nodes are not supported because a preliminary computer run showed the die tended to move away from the support plate at the inner two node locations. This occurs as a result of bending caused by a lack of axial support near the outer periphery. The preload forces of the four bolts used to hold the die in place were neglected for simplicity of analysis, and because their force was negligible compared to the applied pressure load.

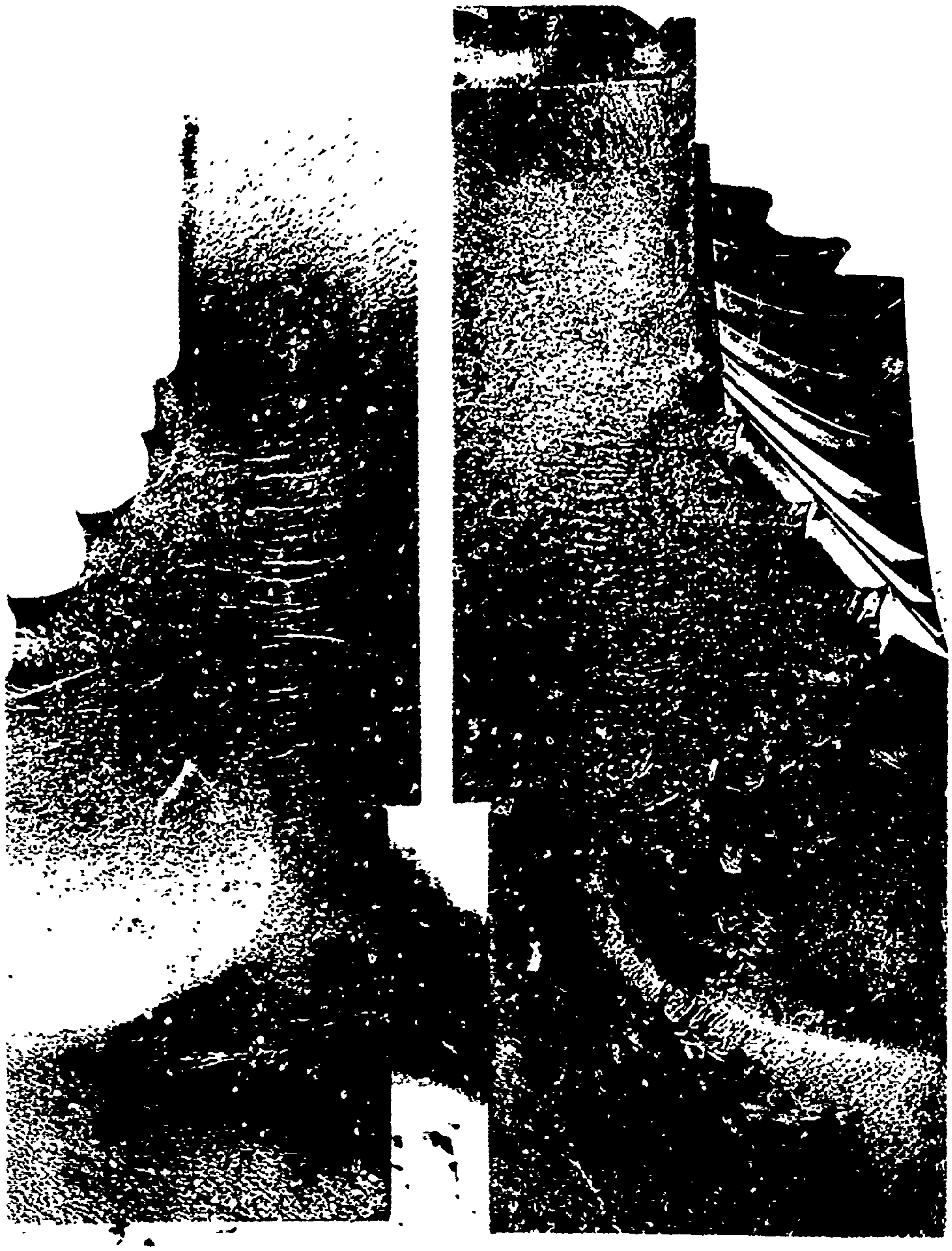


Figure 25. Adjacent fracture surfaces, unetched hot coining die, spiral bevel gears. Scale - full size.

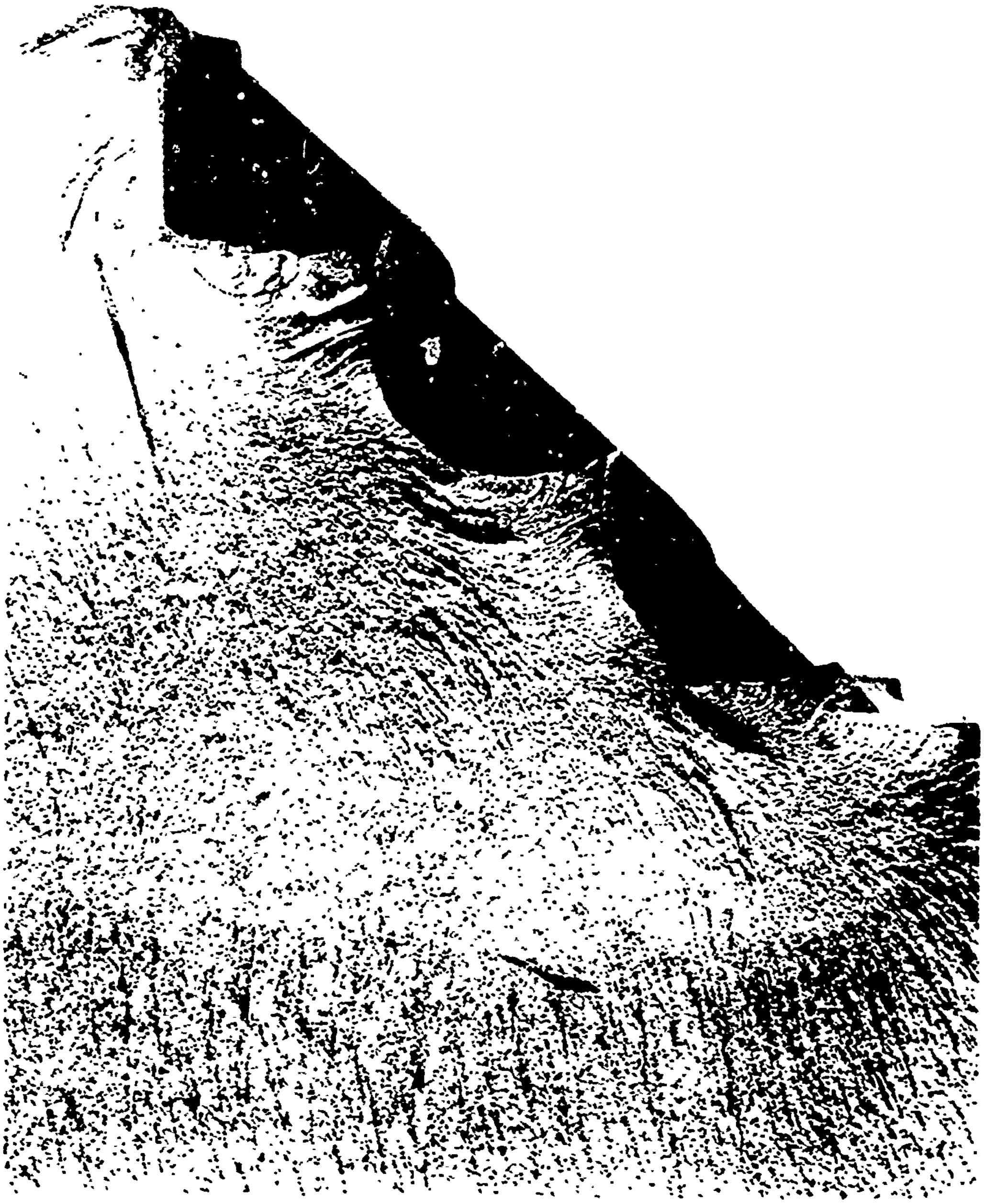


Figure 26. Partial view of fractured section, hot coining die, spiral bevel gear. Scale - 2.5X

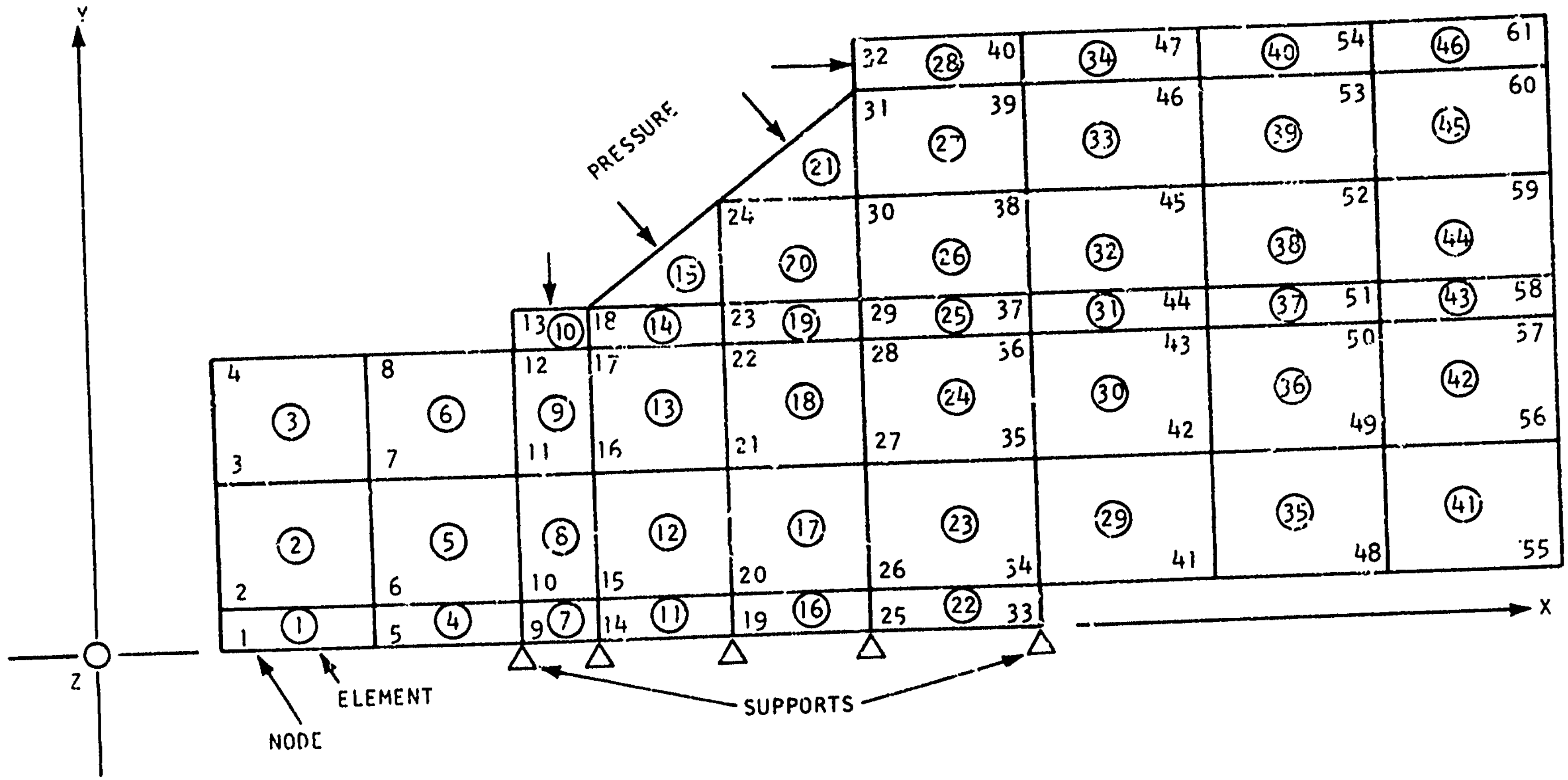


Figure 27. Division of forging die into triangular and quadrilateral toroidal elements for ELAS solution.

Figure 28 presents the hoop stress results obtained with ELAS. Other data indicated that the only significant stress is the 112,000 psi hoop stress at node 4. The material used for the die was H-21 hot work die steel at a Rockwell "C" hardness of 52.5. This indicates an approximate ultimate strength of 265,000 psi. However, because the die material was tempered at 1000°F to obtain high hardness for wear resistance, the impact strength and notch tensile strength were near minimum. Thus, a small flaw at the edge of the inner hole could cause a brittle failure at stress levels near the 112,000 psi calculated.

Since a small hole at the center of a radially loaded plate tends to cause high hoop stresses at the hole, a modified die was analyzed with ELAS to determine the magnitude of stress reduction obtainable by enlarging the center hole and installing a loose fitting bushing to guide the kicker pin. The modified design is shown in Figure 29 with the bushing installed. A die was divided into finite elements for analysis with ELAS. The ELAS results for hoop stress are presented in Figure 30. It can be seen that the maximum hoop stress at the inside diameter of the die has been reduced to 60,000 psi which is almost one half the previous value.

It appears that failure of the bevel gear forging die occurred at the working side edge of the small center hole as a result of hoop stress produced by the forging load. It is not certain if the failure was primarily caused by forging with a piece cooler than the proper forging temperature, or by the presence of a small hole at the center of a die subjected to high radial and bending loads. However, in view of the high notch sensitivity and low impact resistance of H-21 at the 1000°F tempering temperature required for wear resistance, the following changes have been made to the die drawing:

1. Enlarge the center hole to $2.500 \begin{smallmatrix}+.002\\-.000\end{smallmatrix}$ and install a loose bushing to guide the kicker pin. The bushing will incorporate a step for retention.

2. Form a .015" radius at the corners of the enlarged kicker bushing hole to a radius of .010"-.020" will further reduce the maximum stress and eliminate the possibility of accidentally generating a stress riser from a nick in the sharp corner.

3. Refine the tolerances on the bottom surface and the mating receiver to insure a good continuous bearing surface to eliminate any possibility of an extra bending stress.

4.1.4 Gear Form Refinements to Final Configuration

The H-21 and H-26 material gear die blanks were machined to the revised dimensions and heat treated for maximum toughness as described in Section 2.5.

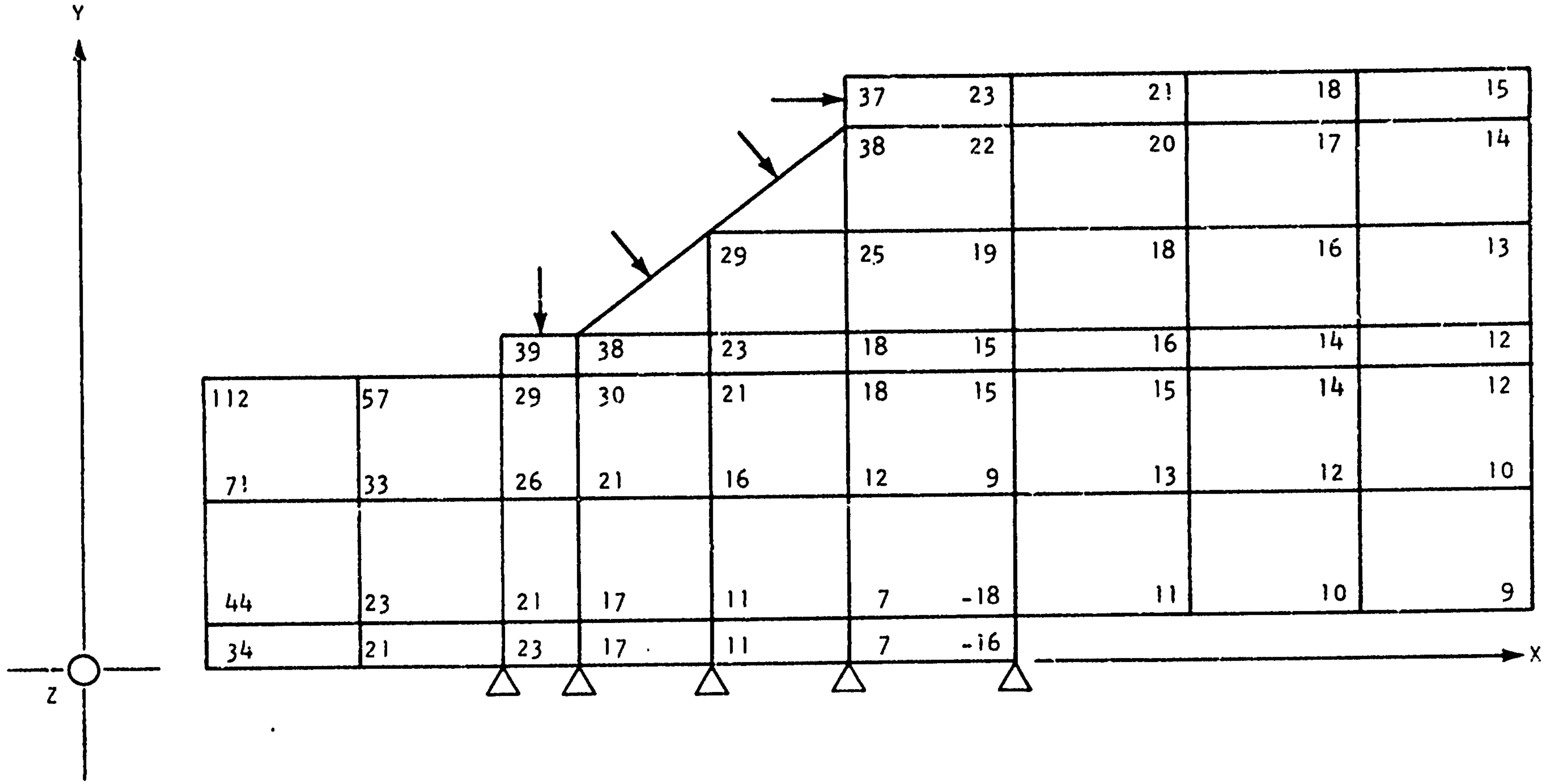


Figure 28. Forging die hoop stresses, ksi.

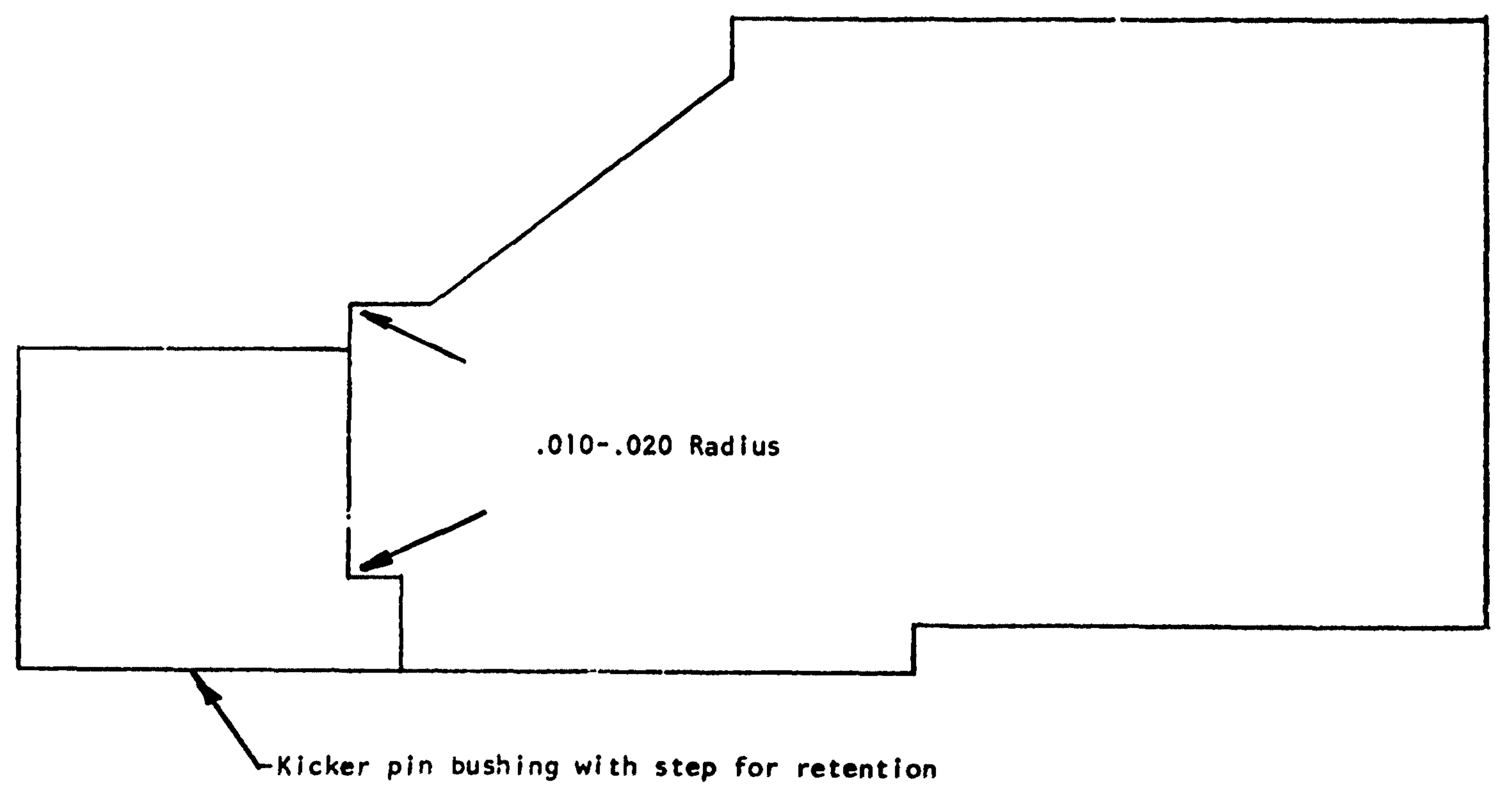


Figure 29. Modified gear forging die.

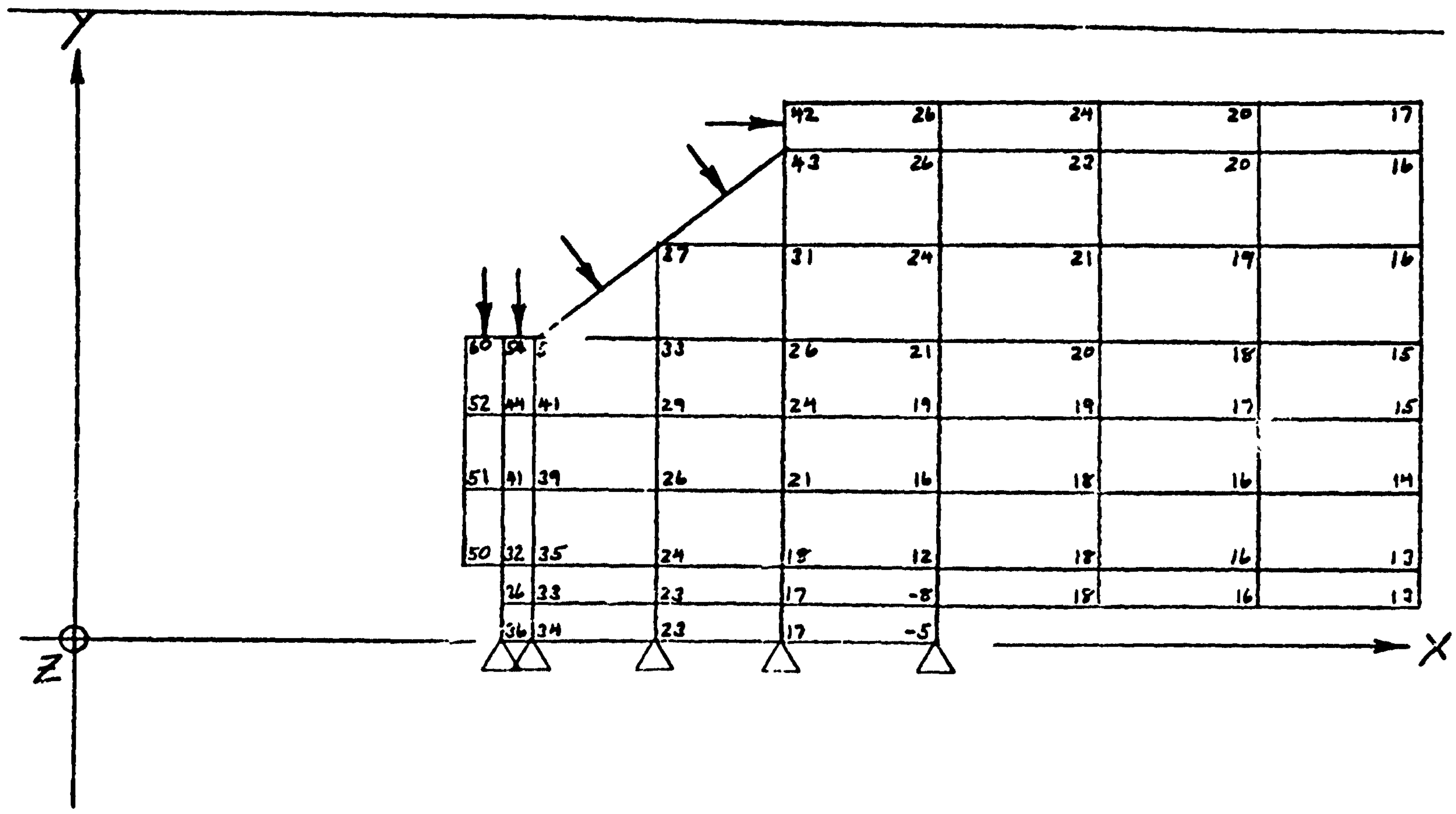


Figure 30. Modified forging die hoop stresses, ksi.

The second development cycle EDM cutting tools were recut to add .010" stock at the toe on the concave side, and .010" at the heel on the convex side, and the gear forging punch was resunk. The die, BF 13774, Detail 15, was resunk to an additional depth of .233" to insure a good tooth form. The same amount of stock was removed from the top of the punch dies to insure proper clearance when installed in the forging press. An additional .250" shim, Detail 4, was added to the bottom of the die to compensate for the thickness change in the punch die. The .017" difference reduced the flash thickness to .150" as desired. This second development cycle was intended to establish the exact billet dimensions as well as the revised gear tooth configuration. The forging process data is given in Table IX.

It was observed that the heating furnace atmosphere was not adequate to prevent the formation of light scale and additional scaling occurred as the part cooled from the forging temperature in air. This indicated the forged tooth surfaces had to be protected from scaling.

An investigation of the billet heating conditions was conducted to reduce the scaling and insure thorough heating. A test billet, representing the mass of the gear forging stock, was fitted with an internal thermocouple located in the center of the piece. The rotary hearth heating furnace was maintained at a temperature of 2050°F and several tests were made to establish the actual time to reach thermal equilibrium. The observed heating times to reach equilibrium was between twenty six and thirty minutes when the furnace was at 2025°F ±25°F. On this basis a minimum heating time of forty minutes was selected to insure a uniform billet temperature.

The Exogas furnace atmosphere generating system was reconditioned and adjusted to deliver 700 ft^{-3} per hour to the furnace. The furnace atmosphere was analyzed and the following composition was maintained:

CH_4 - 0%	CO_2 - 7%
O_2 - 0%	CO - 8%
Dew Point + 40°F	H_2 - 9%

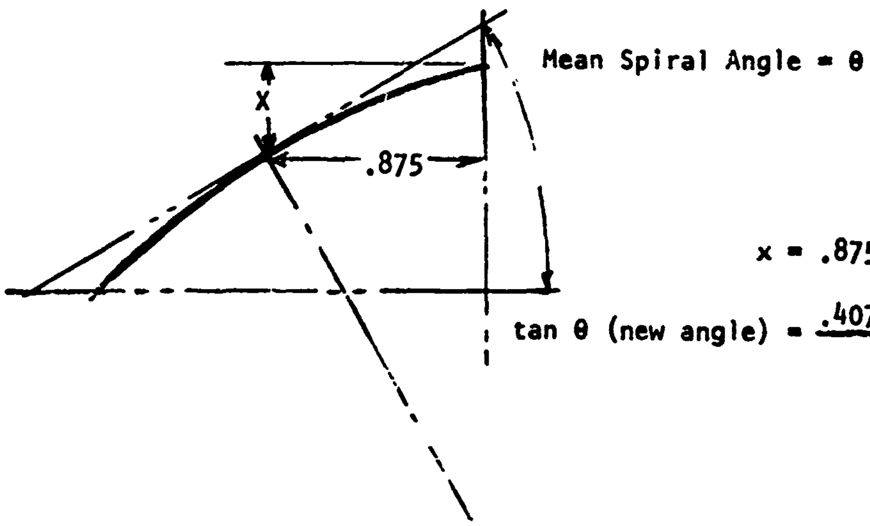
The heating furnace was reconstructed with gas tight seals in all the shell joints. New heating elements were installed and sealed in place. As a result, the atmosphere protected the billets from scaling while in the furnace. Scaling did occur after the billet was removed from the furnace and exposed to the normal environment for working and air cooling. These equipment modifications provided the capacity to process gear forgings at the minimum rate of 20 pieces per hour. This rate was consistent with the production rate planned for the die wear production run.

Table IX

Second Development Gear Forging Data

Forging No.	Material	Size (Inches)	Time in Furnace at 2050°F	Die Temperature °F	Load Cell Reading	Comments
1	1020	3-1/2 diameter x 5-15/16 long	36 minutes	400	Adjusting	No problems forging. Forging scaly.
2	9310	3-1/2 diameter x 5-1/4 long	36 minutes	400	2.6×10^6 lbs.	No problems forging. Forging scaly.
3	9310	3-1/2 diameter x 5-1/4 long	36 minutes	400	2.5×10^6 lbs.	No problems forging. Forging scaly.
4	9310	3-1/2 diameter x 5-5/16 long	42 minutes	400	2.15×10^6 lbs.	No problems forging. Forging scaly.
5	9310	3-1/2 diameter x 5/16 long	36 minutes	410	3.35×10^6 lbs.	Covered with can while in furnace. Stuck in hot coin dies. Surface finish good.

Three representative gear forgings from the second development cycle were selected for evaluation by finish grinding the teeth. The gear tooth profiles cleaned up nearly 100%, but the stock distribution was not uniform along the length of the teeth. A minor modification to the second development EDM electrodes was calculated to equalize the finish grinding stock at both ends of the tooth. The modification was planned to add .005" stock on the tooth profile at the toe end of the concave side (Figure 31). The same amount of correction, .005" was made to add stock on the convex profile at the heel end of the tooth. This modification was made by decreasing the mean 25°-0' spiral angle by 0°-16', derived as follows:



$$x = .875 \times \tan 25° = .40799"$$

$$\tan \theta \text{ (new angle)} = \frac{.40799-.005}{.875} = 24°\text{-}44'$$

Roughing and finishing electrodes were cut with this modification made to the previous settings recorded for the Gleason machine. These third development cycle electrodes were received and a new punch die of H-[illegible]1 steel for the gear was finish machined. The hardness of this die was reduced to Rc 44 from Rc 51 as an extra precaution against cracking.

The tooling for the third development cycle was set up and standard conditions for flash size, temperatures, furnace atmosphere, etc. were established. In this cycle the hot coining work temperature was checked with an optical pyrometer. The forging process starts with the billet at 2025°F ±25°F for preforming. Adiabatic heating due to preforming is balanced against a 30 second cooling time allowed for moving from furnace to preform die, preforming, and transferring from preform die to hot coin die. This balance results in a coining temperature of approximately 1900°F. The forgings produced were of excellent surface quality. The tooth forms were completely filled for the finished gear face width. The die surfaces appeared to be unaffected. No sticking in the die or any other problem was observed in this series of forgings.

The increase in forging force observed in the cycle (Table X) is attributed to the successively larger billet used to produce the planned flash width and thickness. A minor lack of concentricity between the flash and the gear was observed. However, there did not appear to be a correlation between flash eccentricity and filling of the tooth form.

The third development cycle forgings were evaluated by machining as before. The finishing process starts by leveling and clamping the forging in a fixture that locates on the forged teeth. The fixture, Figure 32, is centered in a lathe. The three locating points are clearly shown. The plane of the flash on the gear side is parallel to the plane of the three locators. A series of boring and facing operations then generate the mounting surfaces as calculated from the reference locators. A master cut gear is used to coordinate the set up and achieve the desired results.

Forgings No. 2 and No. 3 of this lot were machined to determine grinding stock left for clean up on the profile of the teeth. Results of this check show that the gear cleaned up nearly 100% except for pits due to scaling. Highest stock removal was .0084" on the heel concave side as shown in Figure 31. The pressure angle change in the 2nd development cycle was correct and did not require an additional alteration of the gear forms.

The spiral angle was to be changed very slightly so that equal stock would be removed over the whole face. It was expected that this change would result in a forged gear tooth configuration essentially congruent to the finished ground gear tooth. Maintenance of congruency is required to achieve acceptable uniformity of the case depth on the finished product.

The inability to make the final minor, but desirable, dimensional adjustment locally in the tooth profile of the forging by the planned "cut and try" approach required that another modification be considered. In an effort to determine the reason why the modifications made to the EDM electrodes and the dies used in the third forging run did not produce sufficient stock for proper clean up, an analysis of the total process was conducted. The analysis of gear geometry was done in great detail (5) considered the following factors:

1. <u>Linear thermal expansion</u> - contraction effects on die and forging.

2. <u>Gear tooth geometry</u> - distortions due to processing temperatures.

3. <u>Gear tooth generating</u> - process as applied to electrode cutting and finish gear grinding.

4. <u>Electrical discharge machining</u> - the relationships between electrode erosion, degree of overburn and control of electrode motion.

Table X

Third Gear Forging Process Development Run

Forging No.	Billet Dimensions (inches)	Heating Time Min.	Furnace Temperature °F	Die Temperature °F	Gear Forging Force lbs.	Remarks
1	3-1/2 diameter x 5.312 long	40	2000	398	2.0×10^6	3/8" heel and toe addendum not filled
2	3-1/2 diameter x 5.312 long	41	2000	415	2.0×10^6	3/8" heel and toe addendum not filled
3	3-1/2 diameter x 5.312 long	53	2050	410	2.0×10^6	3/8" heel and toe addendum not filled
4	3-1/2 diameter x 5.375 long	40	2050	408	2.28×10^6	3/16" heel and toe addendum not filled
5	3-1/2 diameter x 5.375 long	48	2050	407	2.25×10^6	3/16" heel and toe addendum not filled
6	3-1/2 diameter x 5.500 long	40	2050	407	3.7×10^6	Increase preform thickness by .25". Results same as 4 and 5
7	3-1/2" diameter x 5.500 long	41	2050	410	3.3×10^6	Increase preform thickness by .25". Result same as 4 and 5

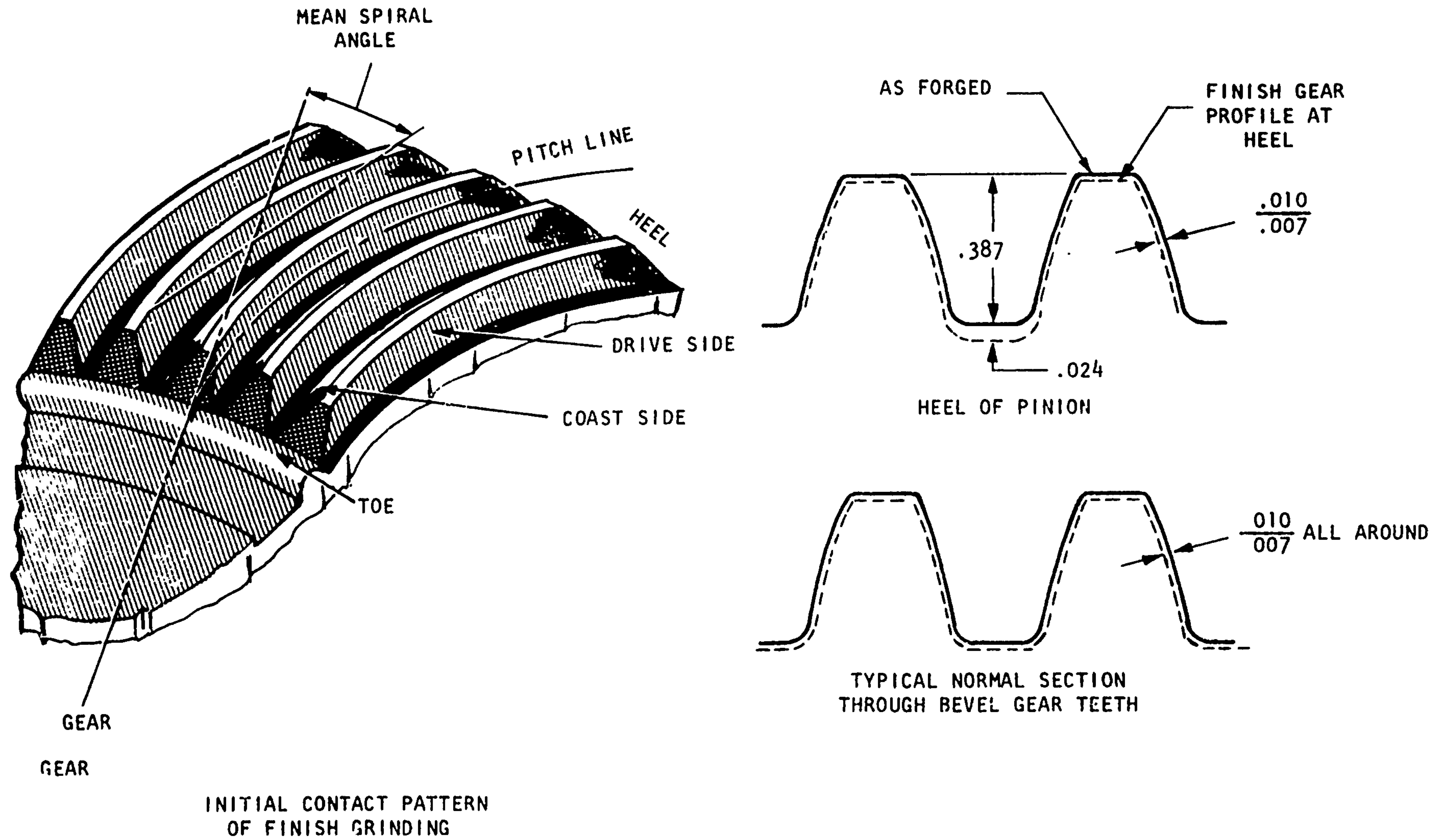


Figure 31. Stock distributions on forged teeth.

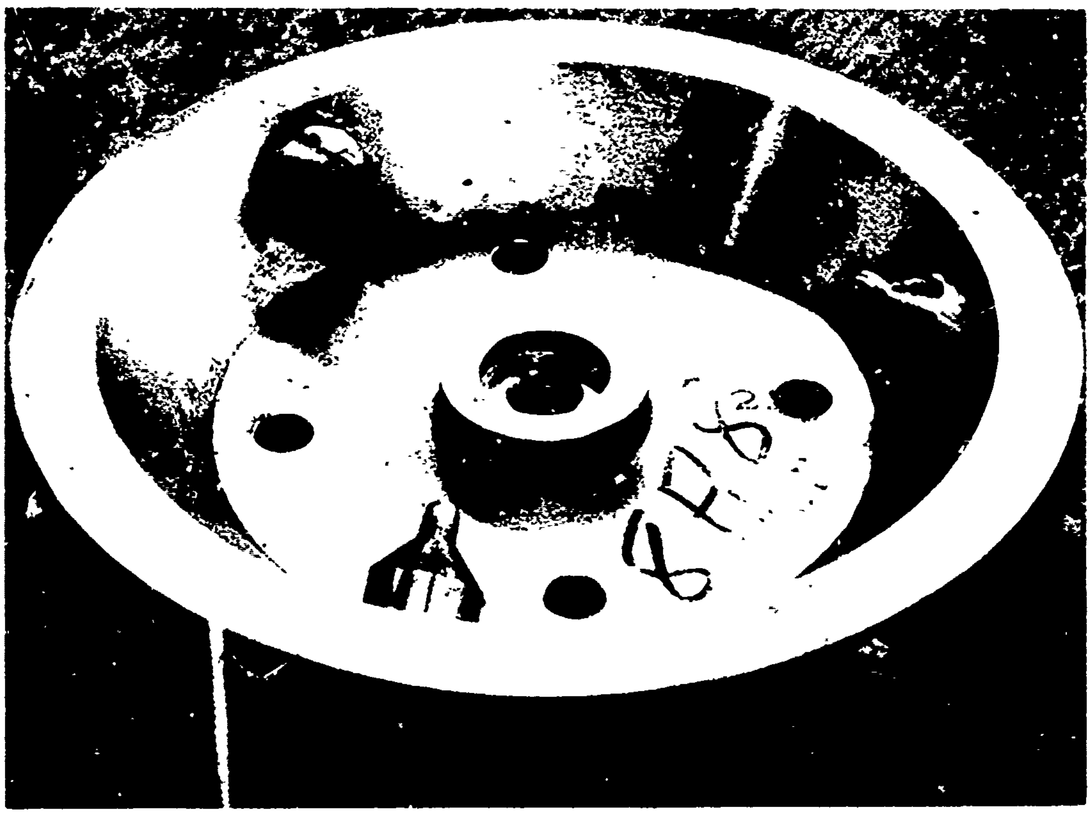


Figure 32. Gear machining fixture locating on pitch cone points.

Stable and homogeneous temperatures were assumed and any transient effects were considered to be inconsequential.

The analysis indicated:

1. The recalculated EDM electrode and forged gear dimensional allowances would be about 30% less than the empirically selected value used.

2. The effect of the above difference is to mislocate the mounting datum surfaces in the gear finished from the forging.

3. This mislocation is the reason the finish grinding operation indicated a change in the spiral angle.

4. The gear teeth could not be properly finished from these forgings without sacrificing some of the benefits of the grain flow lines generated in the forged tooth.

The analysis, combined with a review of the "cut and try" approach confirmed the need for direct measurements of gear characteristics of the die cavity, the EDM electrodes and the forging. A metrology system to do this was developed and adopted for the final development cycle. The system is described in Appendix A.

It was subsequently discovered that the minor corrections that were planned for the third development electrodes were made in the wrong direction. This fact served to demonstrate the need for developing the necessary but unique metrology and of having a quality control activity in a gear development program.

A fourth development cycle, one more than originally planned, had to be performed. The necessary metrology was performed on the electrodes and dies according to procedures described in the Appendix A.

The only discrepancy in the third development forgings was the spiral angle of the teeth. The deviation was in the direction that placed too much stock on the tooth form at the toe of the convex side and the heel on the concave side. The data for the gear and the fourth development electrode are shown in Table XI.

Table XI

Gear Dimensional Data for Fourth Development Cycle

Item	Height "A"	.2500 Ball Dia. "B"	ΔSpiral Convex	at Heel Concave	ΔSpiral Convex	at Toe Concave	Remarks
Cerrabend Molding	+.010	6.545	+.004	-.005	-.001	+.004	
Elect. #3	0	6.514	.000	.000	.000	+.001	3rd Development
Elect. #4	-.010	6.494	+.005	-.005	-.004	+.007	4th Development
Forging 3	-.023	6.463	-.009	+.003	+.006	-.004	3rd Development
Cut Master	.855	6.547	.000	.000	.000	.000	

The changes between the third and fourth developments are clearly shown in the tabulated dimensions for the respective electrodes. The results indicate that the changes have symmetrically distributed the grinding stock on the tooth form. When the die fill and the desired flash size were obtained, twenty-two nickel plated AMS 6265 billets were finish forged. The nickel plating had been applied to protect the forged tooth surfaces from excessive scaling. After forging, the nickel was stripped in 30 minutes by a ferric chloride solution at 120°F. Complete removal of the nickel from the surface was checked by a chemical test. The AMS 6265 material gear forgings were visually inspected and serial numbers 4V16 through 4V25 selected for finishing into test gears.

After completing the forging of the AMS 6265 steel gears, the remaining production quantity of 167 pieces of the AMS 6260 steel gears were forged to conclude the die wear tests. A total of 534 gears were forged on one set of dies with only one resink (EDM machine) of the gear punch die after 367 gear forgings.

The finish grinding operations on the gear teeth confirmed that the dimensions on the forged gear teeth were comparable to those of the production cut teeth (Section 6.0).

4.2 Pinion Forging Development

The basic processing approach and tooling concepts for the pinion forging were established in the planning stage of the program. Details pertaining to pinion tooling or process developments were derived from the experience gained during the gear forging development. This approach avoided parallel and duplicating efforts, and the transfer of feedback experience proved to be efficient. All the major features of the gear development task such as die design, EDM process, die material, etc. have been described in a previous section of this report and will not be repeated here.

The pinion forging tooling, Figure 11, was mounted in the modified 2000 ton mechanical forging press. In this figure the preform die is on the right and the hot coining die is on the left. The set-up was first checked using AISI 1018 steel to refine the starting volume and the die shut height. The billet temperature was 2050°F, heated for one hour in a protective atmosphere.

Satisfactory filling and surface finish was achieved in the first series of tryout pieces. The results are illustrated in Figure 33. The contour of the upset head of the preform shown in this figure is important in positioning the material to fill the coining die without depending on excessive flash, and the resulting higher pressure in the cavity, to promote metal flow. Both operations, preforming and hot coining, are well within the capacity of the press. No force or temperature instrumentation was planned or used in the tooling for the pinion forging process.

A backup preform die punch was designed and fabricated in case the original design failed. The alternate design is a "two piece" punch that eliminated a potential failure at the reduced cross-section as shown in Detail 13, Figure 11. It was calculated that a radial stress of approximately 100,000 psi could be developed by the work trapped in the contoured cavity. This stress, while maximum for that component, is well within the 250,000 yield strength developed in the CH-2 die material. Since the original design functioned as planned, the alternate punch was not used.

The release of the gear teeth by rotation out of the form in the punch was good. One tool design problem that was unsolved in this first round of pinion forging was the kick-out force applied to the finish coined part. The kick-out action from the die was too great in most cases. The 35 pound forging was ejected upward several feet above the die and in most cases resulted in some mutilation of the part as it struck the tooling. This ejection force was then reduced by 25% for the next lot of forgings by reducing the number of Bellvile springs in the system.

After the billet size and tooling had been proven with AISI 1018 and AISI 9310 steels, a run of six 9310 forgings was performed for dimensional evaluation. The forgings were made under the conditions shown in the following Table XII.

Table XII

First Run Pinion Forging Process

Serial No.	Temperature °F	Die Temperature °F	Time in Furnace	Comments: Preform	Comments: Hot Coin
P1	2040	410	40 min.	Hung up 10-15 sec	Over Ejected
P2	2040	410	40 min.	O.K.	O.K.

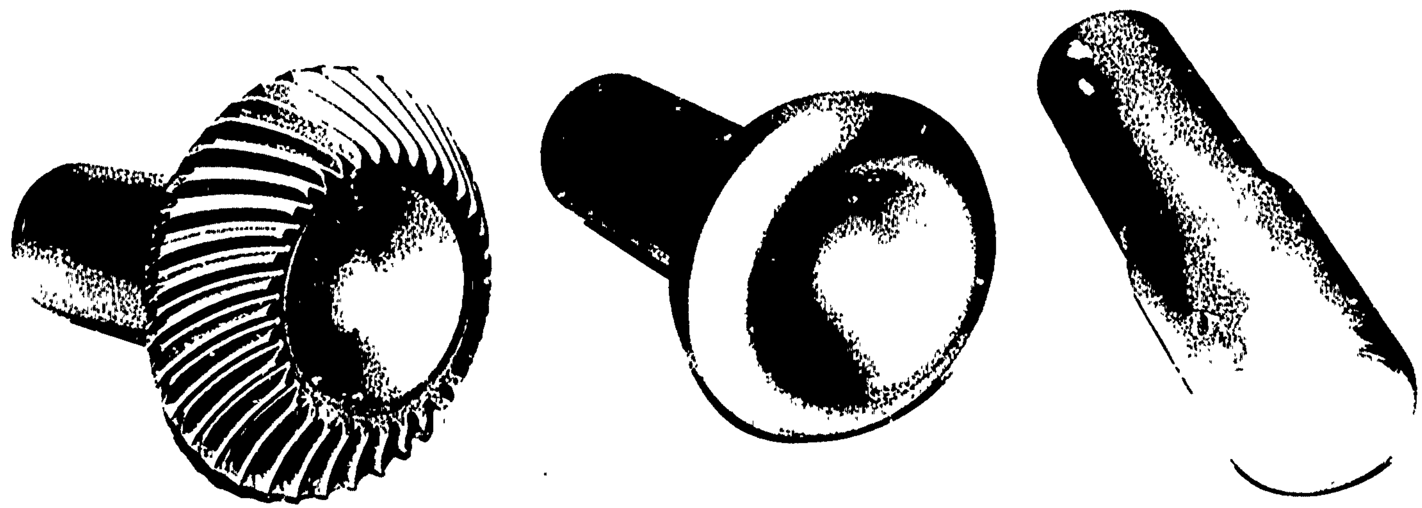


Figure 33. Pinion forging sequence.

Table XII (continued)

Serial No.	Temperature °F	Die Temperature °F	Time in Furnace	Comments Preform	Comments Hot Coin
P3	2025	405	40 min.	O.K.	Over Ejected
P4	2030	420	45 min.	O.K.	Over Ejected
P5	2035	410	40 min.	O.K.	Over Ejected
P6	2040	410	40 min.	O.K.	No Lube Used

The forgings were air cooled and cleaned by a light grit blast and serial Nos. P2, P4 and P6 were selected for machining and grinding for stock distribution evaluation.

Finish grinding revealed that the coast side of tooth form was good. The root depth required an excessive amount of material removal due to an error in the cutting of the electrodes. This error was corrected in the next recutting. A slight change was required in the tooth pressure angle and spiral angle on the drive side to provide a more even distribution of .007" to .010" for stock removal on the carburized gear tooth. The discrepancies were minor for tooth size and form and the whole tooth depth was undersize by about .014". These corrections were incorporated in the new EDM electrodes. The forging design was also revised to allow for additional clean up stock on the thrust face surface and the shaft diameter. These changes were made in the die and die design drawing.

The pinion form was resunk (EDM machined) an additional depth of .135" in order to insure complete tooth clean up to the second development configuration. The top of the punch die was not counterbored or faced off so as to provide for more clean up material on the mounting surface face of the machined forging. The pinion die forging punch was vapor honed in the teeth area using Super Sil abrasive in order to provide a 32 rms surface finish.

The reworked forging dies, BF 13773, were installed in the 2000 ton press and checked for alignment and clearances. The preform die was installed with a .250 spacer in the bottom. The bottom hot coin die was installed with a .254 spacer. The six disc ejector springs were replaced with four disc springs and a .090 filler washer was added to reduce ejection force to 4200 pounds from 6000 pounds. A thermocouple was installed on the top punch dies in order to monitor the temperature.

After the alignment of the dies was proven with some SAE 1020 billets of various volumes, the SAE 9310 steel billets were forged as shown in Table XIII.

Table XIII

Forging Parameters for Second Pinion Development Series

S/N	Weight Pounds	Furnace Discharge Temperature	Die Temperature at Final Hit	Remarks
P7	27.38	2050°F	405°F	Exo gas generator down. Little atmosphere control. Piece scaled but looked fairly good.
P8	27.44			Gas generator out. Piece later removed and scrapped.
P9	27.45	2025°F	400°F	Gas generator replaced. Good atmosphere control. Good forging, no problems.
P10	27.45	2050°F	426°F	Good forging, no problems.
P11	27.43	2050°F	385°F	Good forging, no problems.
P12	27.45	2040°F	420°F	Good forging, no problems.
P13	27.50	2025°F	400°F	Good forging, no problems.
P14	27.50	2050°F	410°F	Good forging, no problems.

All pieces were grit blasted to remove the light scale. Forging numbers P7, P10, P11 and P13 (Table XIII) were selected for evaluation of spiral angle, pressure angle, machining stock and shaft runout.

The selected pinion forgings were set up for machining in a manner that is identical to the method used for the first development series. The results were also nearly identical. There was insufficient material at the toe of the tooth on the concave side. Again the difference was only .005-.007" but could not be explained from the information available. The whole depth of the teeth was .014" undersized.

A check of the EDM electrodes indicated that the corrections that had been planned to correct the root depth and the tooth profile were not incorporated to the extent that had been specified. At this point in time in the program the metrology for spiral bevel gears had been developed and was applied to the pinion development for the third cycle.

The major discrepancies in the second cycle development pinions were:

1. Tooth depth was too shallow by .014".
2. Tooth spiral angle was misaligned by -.004" at the heel of the tooth on the concave side.

New electrodes were cut for this extra development cycle, with the Gleason machines adjusted to correct the above discrepancies. The comparative dimensional results are shown in Table XIV.

A new EDM lead cam was designed and installed on the fixture following the procedures described for the gear (Table XV). The new EDM procedures and the development of the lead angle control cam reduced the amount of stock that had to be removed in the die to completely form the new configuration. The third development configuration was fully formed from the previous cavity with a .047" advance of the electrodes into the die. Formerly about .100" to .125" of stock had to be removed to produce a new configuration.

The third development pinion dies had been judged to be corrected from the comparisons between the second and third development electrodes as shown in Table XIV. The twenty-five machined billets of AMS 6265 steel planned for the required test gears were nickel plated to control scaling on the finish forged teeth. The possibility of a detrimental effect due to nickel diffusion was considered and an investigation was conducted.

A finished pinion forging, made from a nickel plated billet, was subjected to a metallurgical investigation concerned with the carburizing characteristics of the forged tooth surfaces. The forging was stripped of the nickel plate and sectioned through the teeth. This exposed a nickel treated surface and a machined surface to carburizing. The specimen was gas carburized at 1700°F for six hours, then hardened by oil quenching from the austenitizing temperature of 1475°F. Tempering at 275°F for four hours completed the heat treatment of the specimen. It was again cross sectioned to expose the case depths below the nickel treated and the machined surfaces.

The case depth, developed by a nital etch, was a uniform .065" for both surfaces. Microhardness readings were taken at various depths below the surfaces. The effective case depth with a hardness of Rc 58 was -.052" for both surfaces. The maximum hardness of Rc 65 was maintained to a depth of .037". The core hardness was Rc 35/37. From this it was concluded that: (1) the nickel plating and removal would not affect carburizing, (2) the required case and core hardness reading was achieved when the specified procedures were used.

Ten pinion forgings, Nos. 16 through 25, were selected for finish machining. The parts were checked for tooth fill dimensions and appeared to be suitable for finishing into test gears. These forgings were finish machined and were allocated for testing.

Table XIV

Pinion Dimensional Data for Third Development Cycle

Item	Height "A"	.2500 Ball Diameter "B"	Spiral at Heel Convex	Spiral at Heel Concave	Spiral at Toe Convex	Spiral at Toe Concave	Tooth Thickness	Remarks
Cerrabend Molding	-.013	5.490	+.003	+.000	+.001	+.003	.311	
Elect. #2	0	5.462	.000	.000	.000	.000	.308	2nd Development
Elect #3	0	5.467	+.002	-.002	+.003	+.0025	.308	3rd Development
Forging #2	+.027	5.428	-.010	+.006	-.002	-.004	.305	2nd Development
Cut Master	-	5.513	-.007	+.004	+.002	-.002	.302	

Table XV

Third Pinion Development Lead Angle EDM Cam Data at 2.500 Radius

Vertical Position	Rotation to Engage Convex Side - A	Total Back Lash B	Calculated Cam Displacement A + B/2	Tangent of Angle	Angle
0	0				
.002					
.005	.0012	.0003	.0014	.280	15° 40'
.010	.003	.0008	.0034	.340	18° 50'
.015	.0035	.002	.0045	.300	.6° 50'
.020	.0045	.0035	.0062	.310	17° 15'
.025	.005	.0055	.0077	.308	17° 10'
.030	.006	.0070	.0095	.316	17° 30'
.035	.007	.0090	.0115	.329	18° 10'
.040	.008	.0110	.0135	.336	18° 35'
.045	.009	.0125	.0153	.340	18° 50'
.050	.0095	.0145	.0168	.336	18° 35'
.060	.011	.0185	.0203	.338	18° 40'
.070	.013	.0215	.0238	.340	18° 50'
.085	.015	.027	.0285	.336	18° 35'
.100	.018	.031	.0335	.335	18° 35'
.125	.021	.042	.420	.336	18° 35'
.150	.024	.049	.0485	.324	18°
.175	.028	.058	.570	.326	18° 50'

Calculated mean lead angle 17° 50'

5.0 PRODUCTION FORGING PROOF PHASE

The gear forging tooling, BF 13774, from the third development cycle was used for this die wear test. The gear forging die was checked for cracks by magnetic particle and dye penetrant inspection techniques. A cast was made for the record of the form in the die cavity. The tooling was set up in the 2000 ton mechanical press with instrumentation to record the forging force and the die temperature of the finished hot coining die. The billet size and die set up adjustments were the same as those established for the third gear development cycle.

Semiproduction conditions were established for the heating cycle and the work handling. Refined billet feeding and transfer tooling to optimize the production rate and labor utilization was not within the scope of the die life test. However, an Industrial Engineering survey was conducted and a temporary labor standard was established for use in an overall cost analysis that was performed at the end of the development program. The observed rate of production for this run was limited by the heating capacity to 8-1/2 pieces per hour.

The nominal operating conditions for the gear production forging run were as follows:

Material - AMS 6260, hot roll finished bar

Billet Size - 3-1/2" diameter and 5-1/2" long

Heating Temperature - 2025°F ±25°F - 45 minutes

Endo - gas flow (7:1 ratio), 700 cubic ft/hour

Die Temperature - 400°F

Die Lube - 5% AQUA-DAG, 5 second spray

Transfer Time Furnace to Preform Die - 10 seconds, average

Transfer Time Preform Die to Coin Die - 12 seconds, average

Observed Coining Temperature - 1900-1950°F

Coining Load 3.5×10^6 lb.

Minimum heating time is about 45 minutes per billet. Thus, to maintain uninterrupted production the furnace capacity would have to be at least 60 billets. On a continuous basis then, the production rate would be 120 forgings per hour. The billet weight is approximately 15.5 pounds each. A furnace with a heating capacity of 1860 pounds per hour is required for this production rate.

An alternate induction heating method was considered. It is readily adaptable to a continuous feeding process, through the induction heating unit, directly into the preform die. One arrangement is to provide the unit with a through feed coil and automatic stock pusher. The capacity of induction units are normally rated at about 50 pounds per hour per kilowatt. A standard 30 KW unit has a capacity of approximately 1500 pounds per hour, equal to 100 pieces per hour, on a continuous basis. Thus, as the workpiece becomes larger in size and weight, the heating device may become the system element which limits productivity. This preliminary analyses of alternate heating methods are made only to estimate potential production rates. The demonstration of a robot heating-transfer system was beyond the scope of this program but the known state-of-the-art for such a system is available. The 500 piece production lot was scheduled to run on consecutive days until die wear was detected. The finished forgings were sequentially serialized. Serial numbers 1, 2, 25, 50, 75.....342 were selected for detailed measurement to evaluate die wear.

The accuracy of the measurements depends on the smoothness of the surface being checked. Some scaling of the surfaces could not be avoided since the forgings were cooled in air after coining. The scaling resulted in a fairly uneven surface. Also the rough outside diameter of the 3-1/2" billet formed the surface in some areas of the gear teeth. To eliminate this variable in later measurements, billet Nos. 300 and 342 were ground on the O.D. and nickel plated to eliminate the scale. After forging, these parts presented very smooth surfaces for measurement.

All operating conditions were observed and recorded for each forging throughout the test. The surface of the die was visually inspected after every 25th piece. At about the 300th piece the projections in the die appeared to be developing a slightly rough surface.

The die wear test was arbitrarily stopped at the 342nd part. The decision to stop the test was based on a conservative approach and a desire to avoid an extensive breakdown of the die. The first die life goal of 250 pieces, set for economic effectiveness was met. The same die had been selected for the fourth development forging and it was desired to minimize the amount of stock removed in resinking the form. Forgings numbered 1, 2, 25, 50, 75... ..342, etc. were cleaned by grit blasting and submitted for dimensional inspection.

To obtain a permanent record, a cast was made of the die cavity after the die was removed from the press after the forging of the 342nd piece. The die was re-inspected for surface and internal defects by NDT methods and no failures were detected. All the finished forgings were stocked for disposition (see Figure 34).

The fourteen forgings selected for dimensional i -pection were checked in accordance with the procedure described in Appendix A The EDM electrode used to finish the die cavity, and the casts made of the ity before and after the run, were also inspected. The open set-up inspection methods used are illustrated in Figures 35 through 41. Two readings were taken and recorded for each dimension. See Appendix A for a description of the characteristics which were measured and documented.

Figure 34. Production run forging for die wear evaluation.

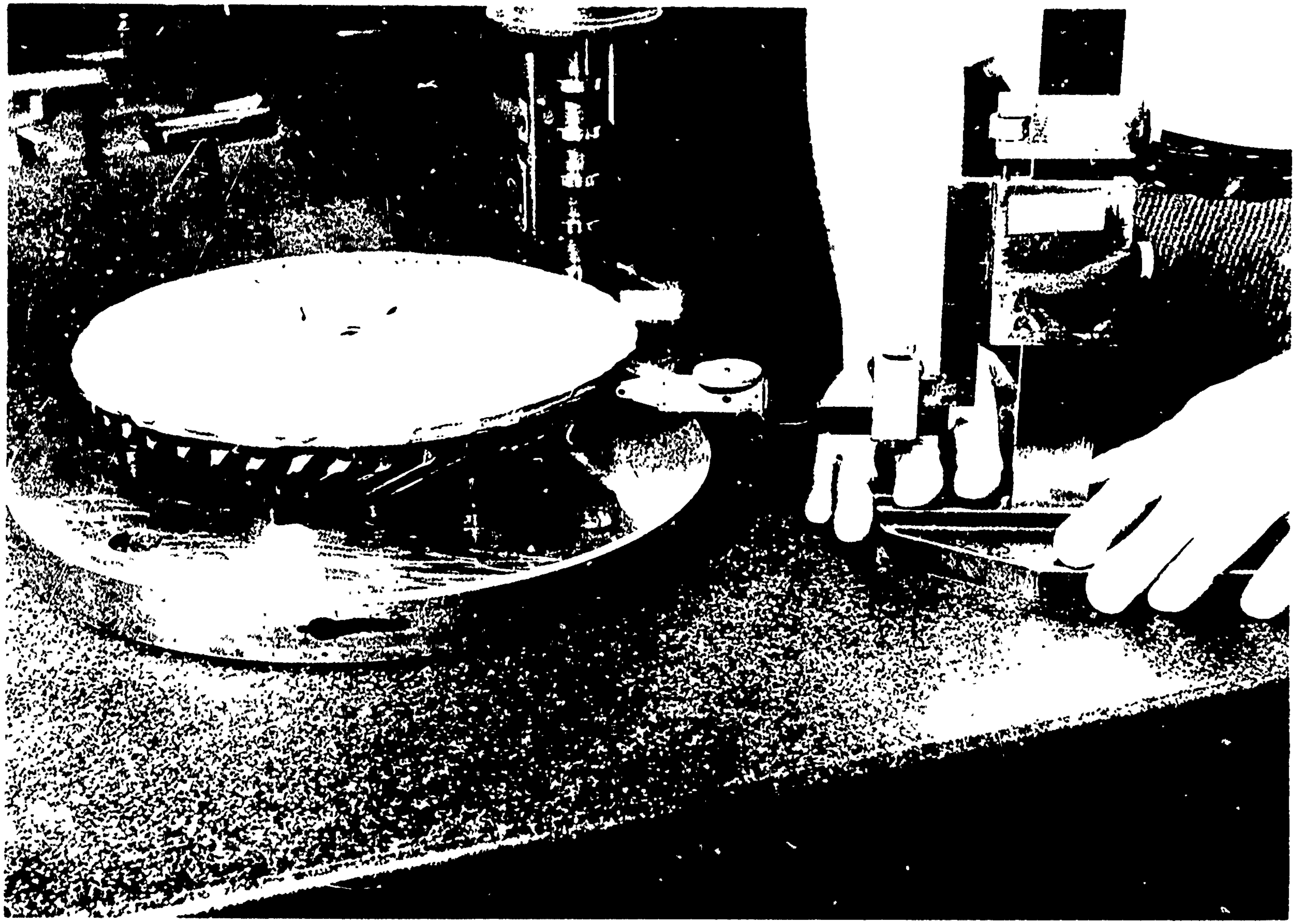


Figure 35. Cast set-up for inspection of "A" dimension.

Figure 36. Checking the "B" dimension on a forging.

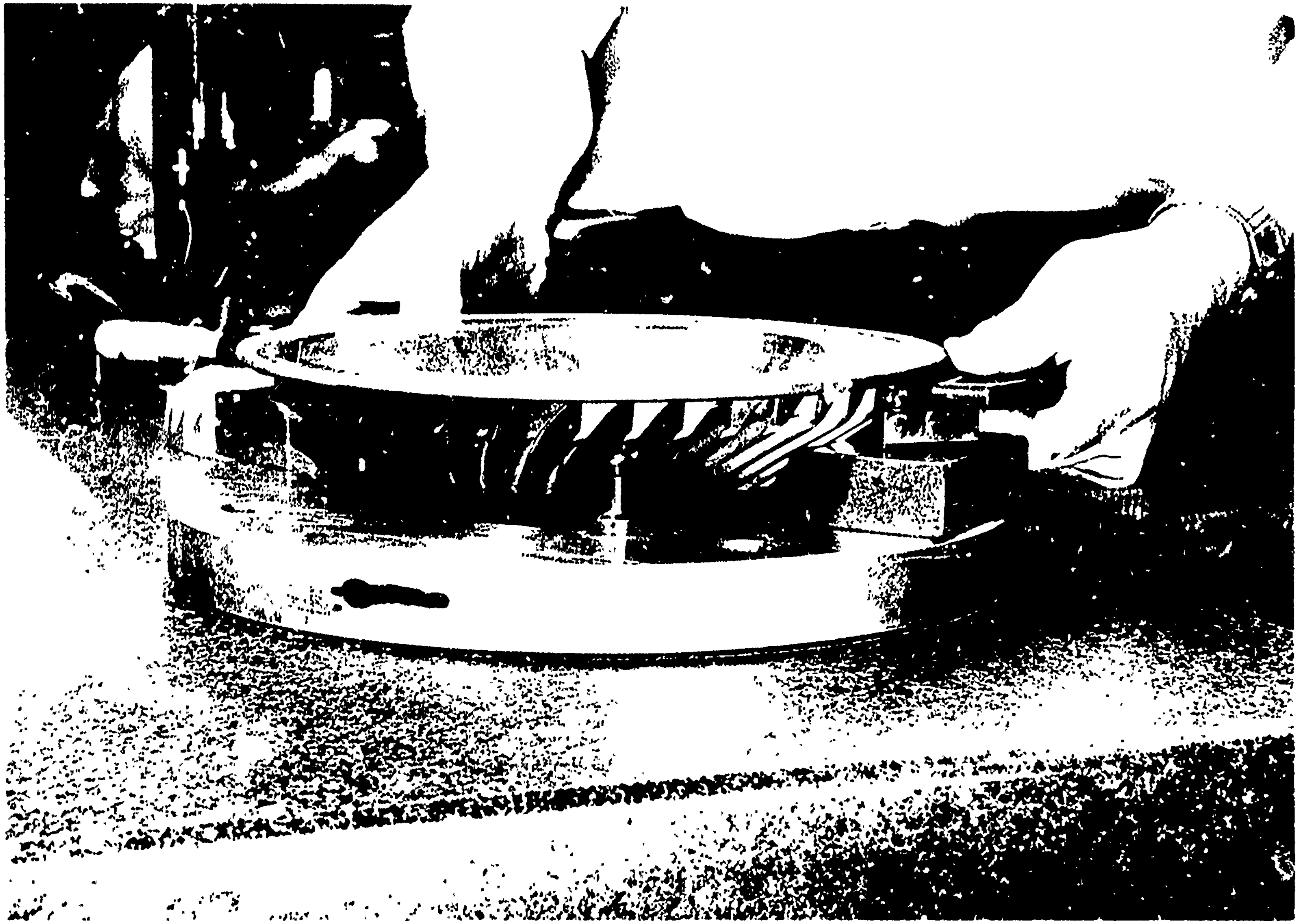


Figure 37. Checking the "C" dimension on a forging.

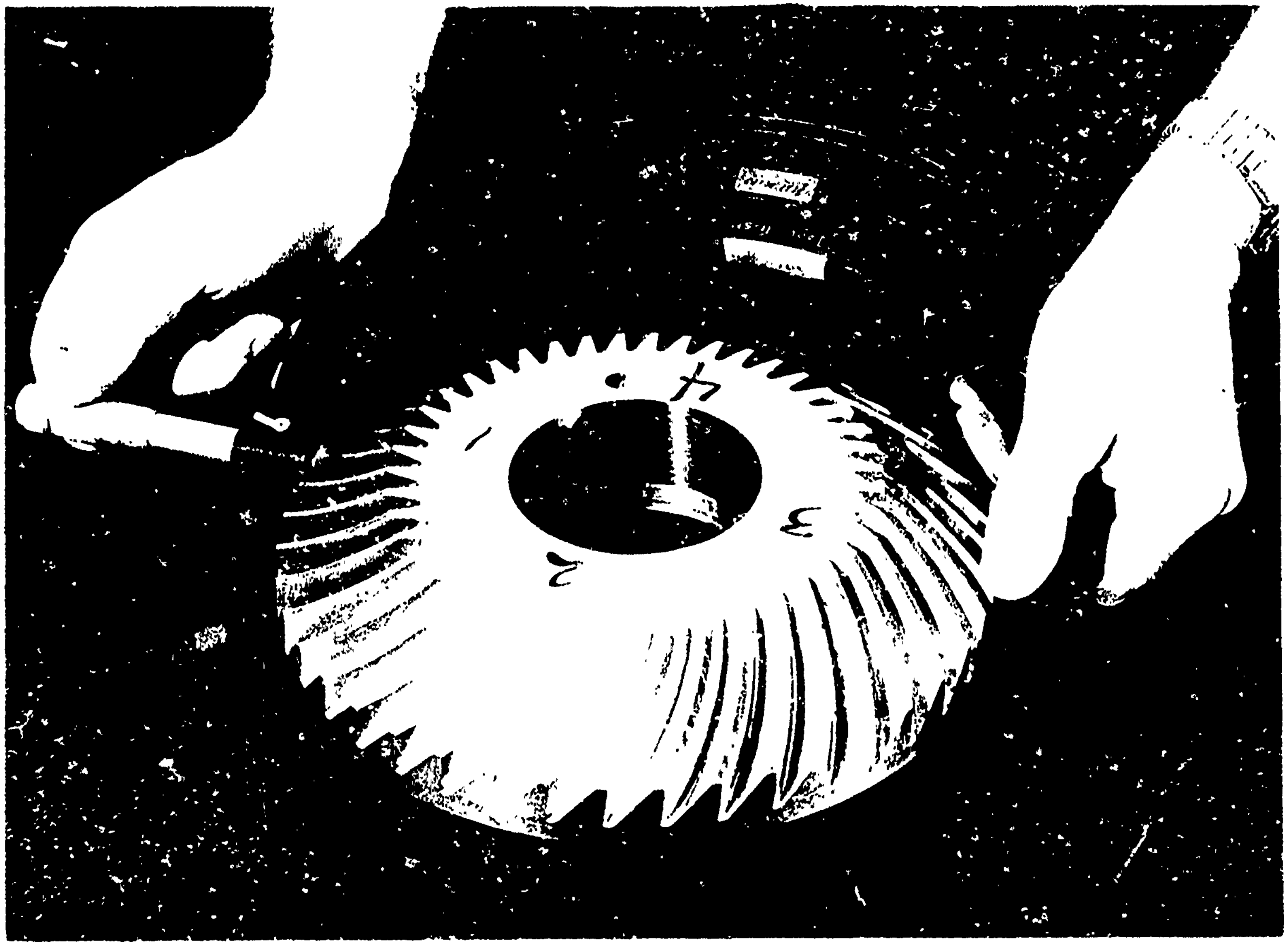


Figure 38. Checking the "D" dimension on the electrode.

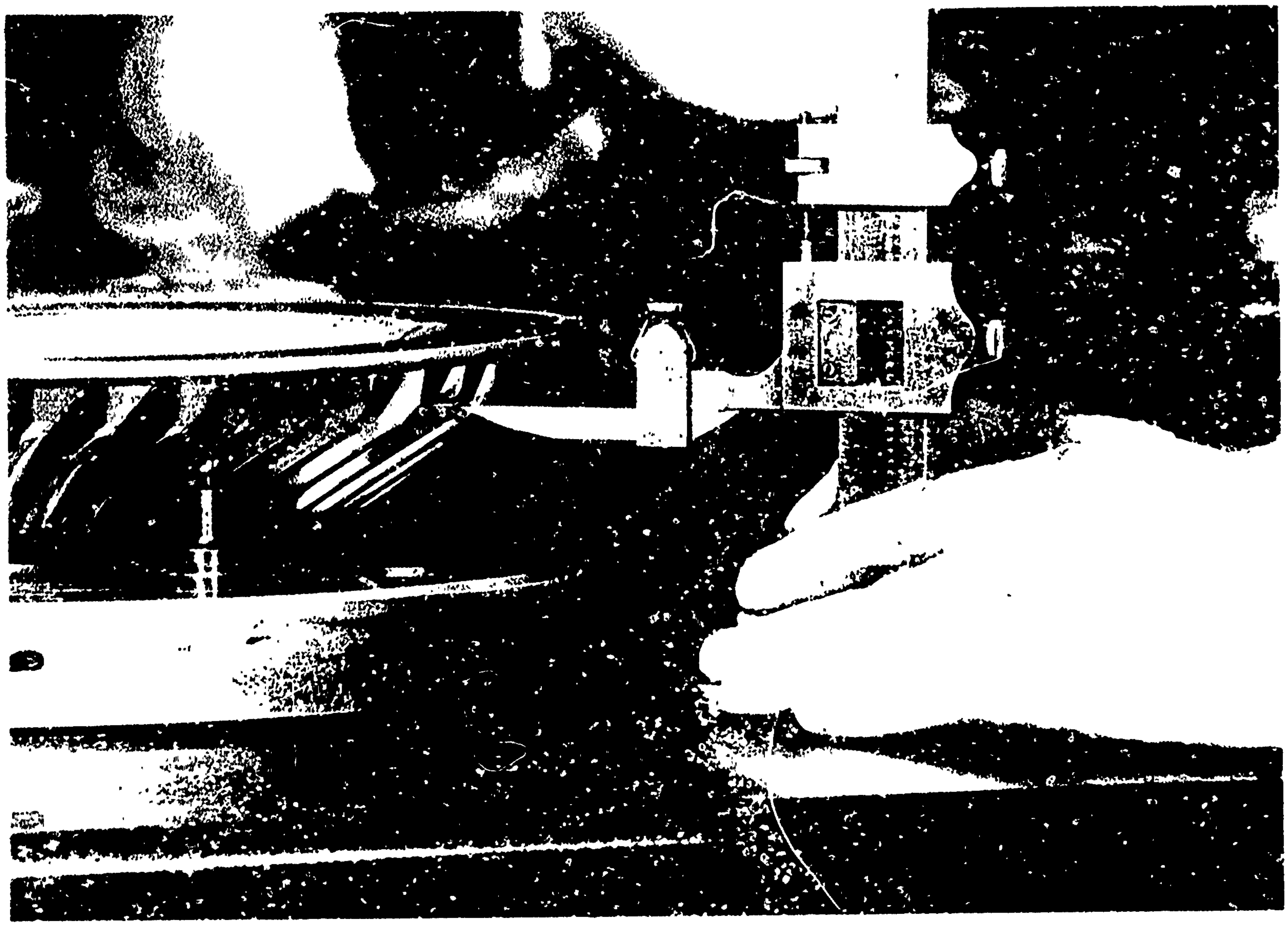


Figure 39. Marking plane for tooth thickness check on forging.

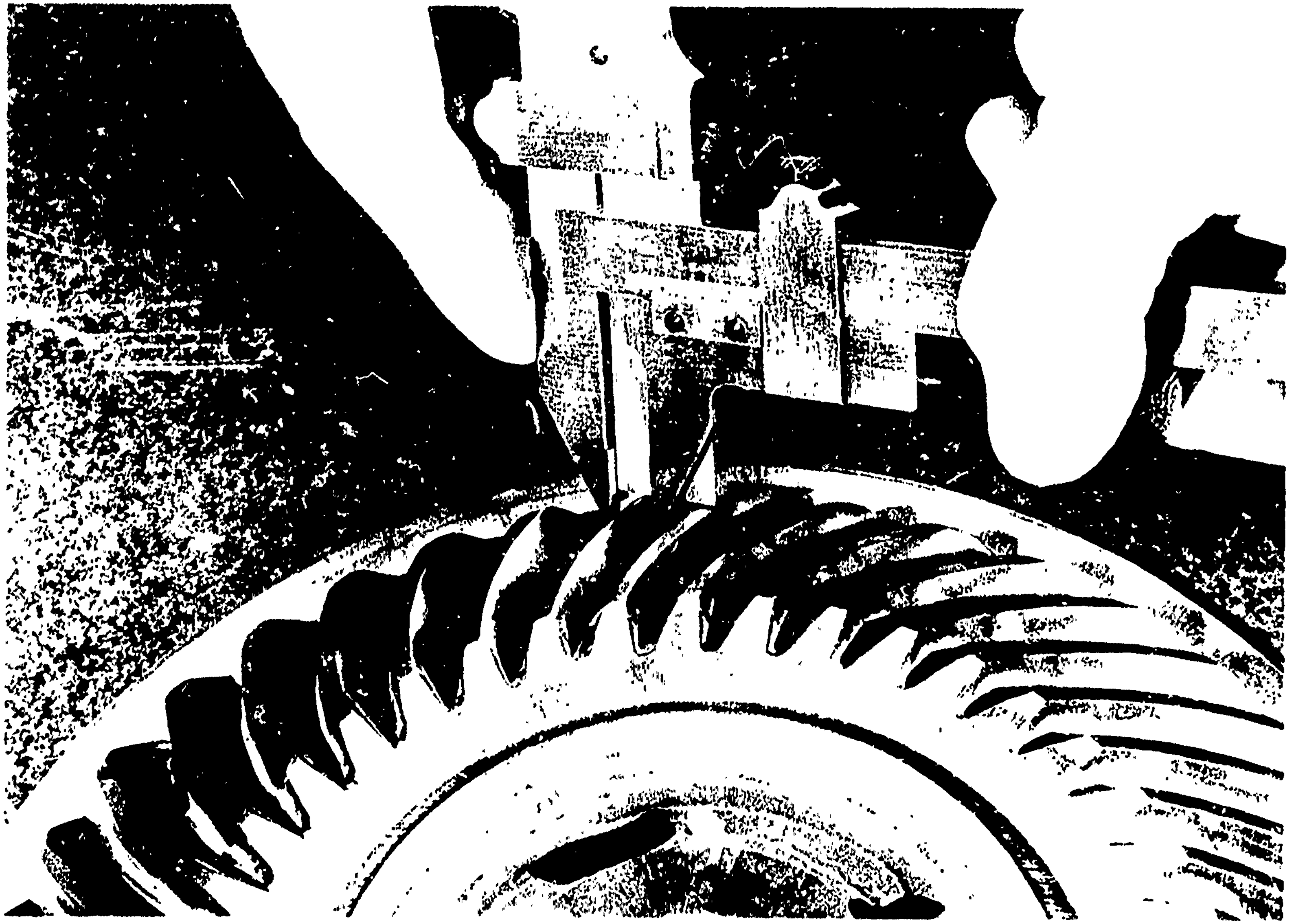


Figure 40. Measuring tooth thickness of forging.

Figure 41. Measuring whole tooth depths and addendum on forging.

The gear dimensions that are directly affected by die wear are "B", "C" and "A". The diameters "B" and "C" increase at a ratio of 5:1 with die wear, i.e., for each mil added to the tooth surface, the diameter measured over balls will increase 5 mils for the 22 1/2° pressure angle tooth design. Table XVI shows the calculated relationship between tooth stock and pitch diameter. The raw data did not indicate a pattern that could be associated with progressive size changes caused by die wear. The data were then statistically analyzed and organized in Table XVII. An examination of these data indicated that no significant amount of die wear occurred.

The whole tooth depth dimension is an inverse 1:1 measure of wear of the projections in the gear die form that determine the tooth root radius and root cone angle on the forging. An increasing negative value for this dimension indicates the die wear rate. These values are tabulated in columns eleven through sixteen of Table XVII and the deviations are plotted in Figure 42. The measurements taken of the addendum are affected by die wear in two locations: (1) wear on the flank will thicken the forged tooth and reduce the reading and (2) the gage locates on the tooth tip cone but wear of the die in this area is minimal.

The forging run of 342 pieces was not enough to wear the die to a measurable extent. The trends in these measurement data, if they exist, could be obscured by the relatively large errors that appear to occur in the measurements. This assumption is based on the observation of several measurements with large deviations from those taken on other forging parts near it in the series. If these aberrations were deleted the conclusions would not be greatly influenced since the variations are compensating.

In addition to the controlled production run, approximately fifteen development forgings were made on the same die, for a total of 357 pieces. Since neither surface wear nor failure by surface cracking was observed, a die life of 500 pieces is a conservative goal and prediction.

After the fourth development cycle was completed and proven and twenty-five gears for testing were forged, another production run was initiated. The forged gears with assigned serial numbers 4-1 through 4-167. A cast was made of the die cavity before and after the run. Approximately every twenty fifth forging in the series was inspected dimensionally after removing the scale. Eight forgings, with serial numbers as shown in Table XVIII, were dimensionally inspected using procedures and gages described earlier. The results are tabulated and plotted in Figure 43. Die wear will displace the first four characteristics plotted in Figure 43 toward the minus values from the reference axis. The reference axes selected in the figure is the root mean square of the measurements and the deviations from rms are plotted. This technique for handling the data tends to compensate for variations introduced by gaging methods. The gaging method used is not optimum and is not repeatable to less than ±.001". The results are dependent on the inspector's "feel" as well as some random effects of positioning and local surface roughness.

Table XVI

Calculated Pitch Diameter Change with Tooth Thickness Change
22-1/2° Pressure Angle Involute

Pitch Diameter Change	Tooth Thickness Change	Stock on Gear Surface
.008	.0032	.0016
.012	.0046	.0023
.016	.0062	.0031
.020	.0076	.0038
.024	.0092	.0046
.028	.0106	.0053
.032	.0122	.0061
.036	.0138	.0069
.040	.0152	.0076
.044	.0618	.0084
.048	.0184	.0092
.052	.0200	.0100
.056	.0214	.0107
.060	.0230	.0115
.064	.0244	.0122
.068	.0260	.013

Table XVII

Dimensional Inspection Statistical Data

Column No.	Gear No.	Die Temp. °F	"B" Toe Diameter	Deviation mils	"C" Heel Diameter	Deviation mils	"D" Gear O.D.	Deviation mils	Addend. Depth	Deviation mils	SK-103071JH Gage Readings: Whole Tooth Depth: Toe	Deviation mils	MPD	Deviation mils	Heel	Deviation mils	"T" Tooth Thickness	Deviation mils	Height to Flash	Deviation mils	"A" Height to Face	Deviation mils
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
	1	400	6.752	0	9.209	-1	8.956	-11	.614	-4	.558	+3	.507	-1	.486	+8	.316	+8	3.081	-3	1.5225	0
	2	405	6.743	-9	9.221	+11	8.955	-12	.632	+14	.568	+3	.511	+3	.479	+1	.300	-8	3.0835	0	1.519	-4
	25	405	6.753	+1	9.206	-4	8.968	+1	.611	-7	.553	-2	.509	+1	.478	0	.305	-3	3.0835	0	1.5225	0
	50	390	6.745	-7	9.188	-22	8.955	-12	.614	-4	.554	-1	.510	+2	.476	-2	.320	+12	3.075	-9	1.517	-5
	75	410	6.750	-2	9.198	-12	8.946	-21	.614	-4	.551	-4	.506	-2	.478	0	.314	+6	3.071	-13	1.5275	+5
	100	409	6.747	-5	9.207	-3	8.961	-6	.613	-5	.554	-1	.511	+3	.486	+8	.310	+2	3.0875	+3	1.5205	-3
	127	415	6.755	+3	9.211	+1	8.973	+6	.614	-4	.557	+2	.508	0	.477	-1	.304	-4	3.086	+2	1.5215	-1
	150	410	6.759	+7	9.214	+4	8.976	+9	.612	-6	.550	-5	.506	-2	.474	-4	.323	+15	3.090	+6	1.527	+4
	175	405	6.749	-3	9.208	-2	8.973	+6	.614	-4	.551	-4	.507	-1	.473	-5	.321	+13	3.086	+2	1.520	-3
	200	400	6.755	+3	9.197	-13	8.974	+7	.629	+11	.557	+2	.509	+1	.478	0	.298	-10	3.087	+3	1.534	+11
	250	420	6.758	+6	9.211	+1	8.974	+7	.640	+22	.554	-1	.505	-3	.468	-10	.300	-8	3.086	+2	1.5245	+1
	275	420	6.755	+3	9.253	+43	8.977	+10	.615	-3	.553	-2	.511	+3	.481	+3	.300	-8	3.089	+5	1.523	0
	300	390	6.746	-6	9.215	+5	8.974	+7	.611	-7	.554	-1	.507	-1	.475	-3	.300	-8	3.083	-1	1.5255	+3
	342	405	6.755	+3	9.210	0	8.973	+6	.625	+7	.554	-1	.510	+2	.478	0	.296	-12	3.0855	+2	1.5185	-5
RMS C Std. Dev.		406	6.752	±5	9.210	±15	8.967	±10	.618	±9	.555	±4	.503	±2	.478	±5	.308	±9	3.084	±5	1.523	±4
	#1 Plastic Mold		6.759		9.232		9.059		.6055		.549		.546		.452		.285					
	#342 Plastic Mold		6.761		9.217		9.036		.608		.548		.508		.470		.283					
	Electrode		6.756		9.268		9.119		.592	1	.534	±1	.492	±1	.462	±.1	.278	±2	Top of Electrode 3.536		1.531	

Table XVIII

Dimensional Inspection Statistical Data for Gear Fourth Development

	Gear No.	"B" Toe Diameter	Deviation mils	"C" Toe Diameter	Deviation mils	Gear O.D.	Deviation mils	P.D. Addendum	Deviation mils	Whole Tooth Depth Heel	Deviation mils	MPD	Deviation mils	Toe	Deviation mils	Tooth Thickness	Deviation mils	"A" Dim. Loc. to Face	Deviation mils
Column No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
	4-3	6.455	+1	8.748	-15	8.972	-8	.609	+4	.548	+2	.496	-1	.467	2	.259	-5	1.151	+18
	4-25	6.448	-3	8.760	-3	8.969	-11	.603	-2	.543	-3	.496	-1	.458	-7	.262	-2	1.129	-4
	4-50	6.451	0	8.765	+2	8.984	+4	.605	0	.542	-4	.498	+1	.468	+3	.267	+3	1.126	-7
	4-75	6.447	-4	8.760	-3	8.972	-8	.606	+1	.542	-4	.496	-1	.468	+3	.263	-1	1.123	-10
	4-100	6.450	-1	8.763	0	8.984	+4	.608	+3	.548	+2	.498	+1	.464	-1	.261	-3	1.160	+27
	4-125	6.452	+1	8.777	+14	8.990	+10	.604	-1	.545	-1	.499	+2	.465	0	.267	+2	1.114	-19
	4-150	6.452	+1	8.764	+1	8.981	+1	.603	-2	.554	+8	.497	0	.467	+2	.265	+1	1.123	-10
	4-167	6.450	-1	8.770	+7	8.984	+4	.604	-3	.547	+1	.494	-3	.461	-4	.269	+5	1.136	+3
RMS		6.451	±2.5	8.763	±8	8.980	±8	.605	±2	.546	±4	.497	±2	.465	±4	.264	±3	1.133	±16
	#1 Plastic Cast							.601		.543		.494		.461		.2582			
	#4 - 167 Plastic Cast							.599		.543		.495		.459		.2595	+1.5		

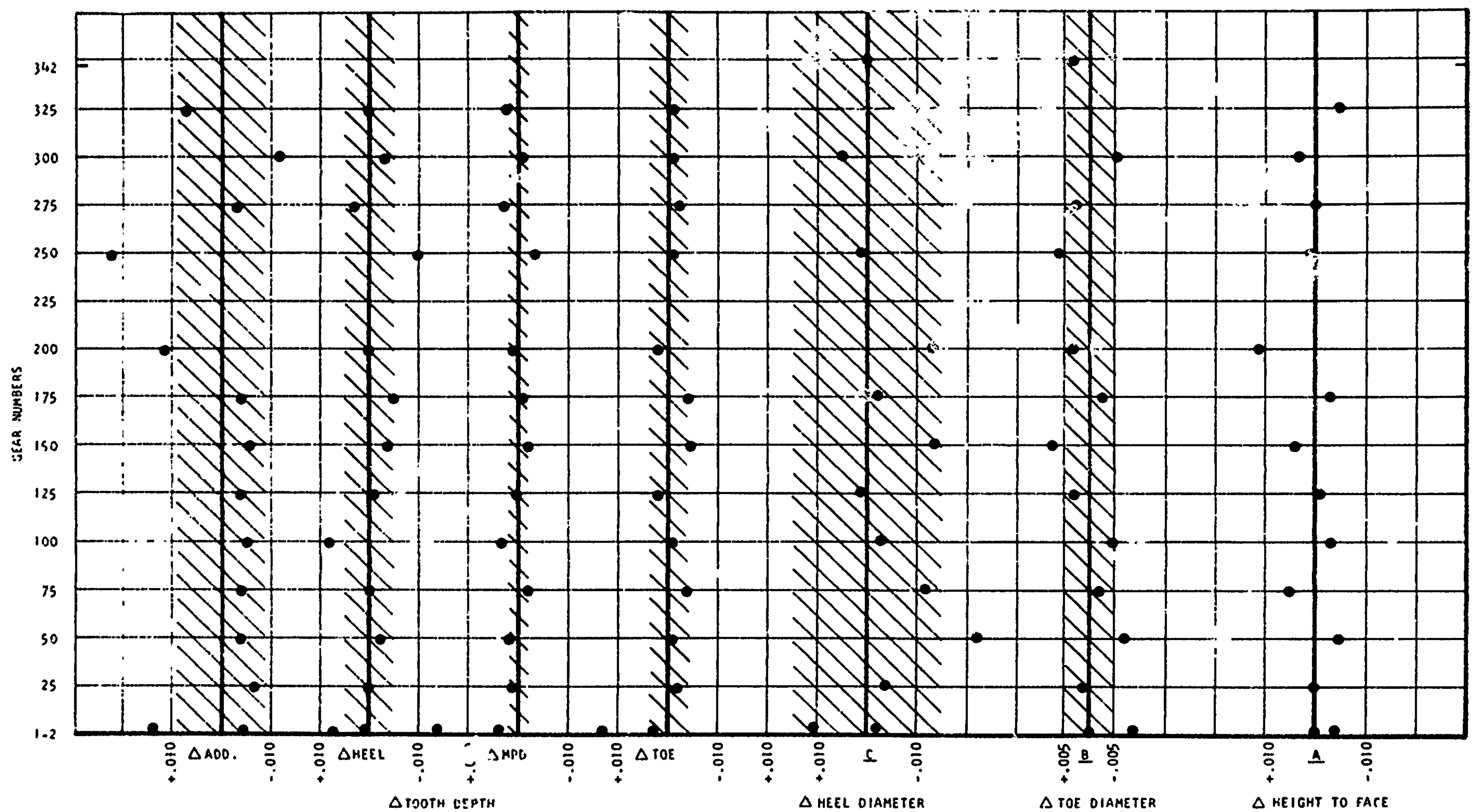


Figure 42. Plot of dimensional deviations caused by die wear.

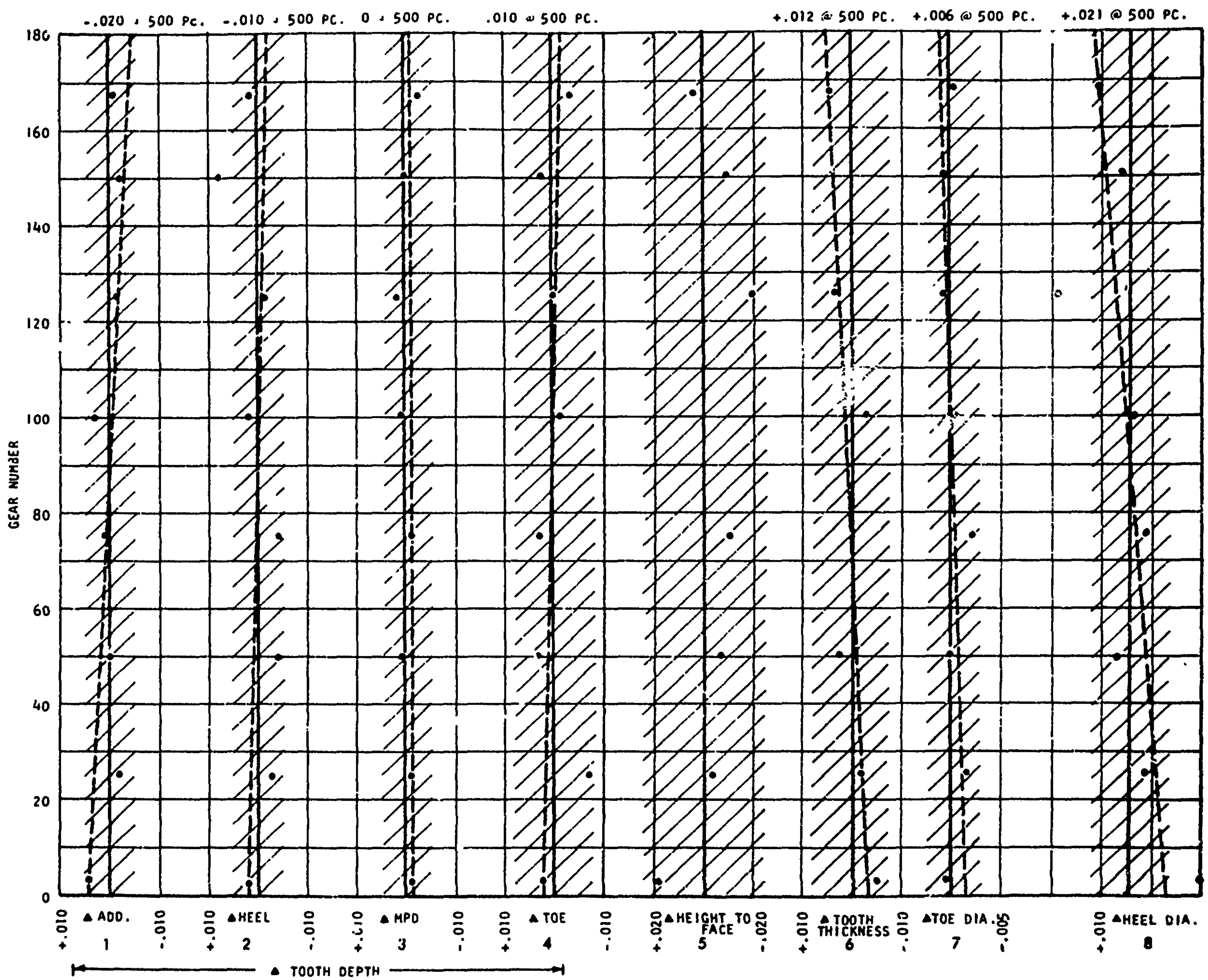


Figure 43. Plotted dimensional deviations and extrapolations.

A trend in the recorded forging dimensions, as an indication of die wear, cannot be clearly identified. One attempt to fit a curve to the plotted points, with the initial reading as the origin, will indicate die wear by the negative slope of the line for the first, second and fourth characteristic in Figure 43. No die wear can be shown by the measurements taken of the whole tooth depth at the mean pitch diameter by interpreting the data as the deviation from the rms, or by curve fitting starting with the first recorded dimension as the original size.

The characteristic identified as "height to face" is the "A" dimension shown in Figure 1A in the appendix. Die wear will result in thicker forged teeth and "A" will increase or tend toward greater positive deviations. The trend cannot be detected in the data taken from this production series of gear forgings.

The tooth thickness measurement, taken on a tapered cross section, is difficult to define and measure on a spiral bevel gear. It is not normally an independently controlled dimension in the production of spiral bevel gears. However, in the forging process it is the one most directly affected by die wear. The results of the tooth thickness measurements does indicate a trend to the positive side of the rms with the number of parts formed. Extrapolating this trend to five hundred pieces indicates an increase of .012" in tooth thickness or .006" per side. This range is within the manufacturing tolerance used to control the amount of stock removed from the tooth profile and will result in the desired final hardened case depth. Extrapolations of other dimensional changes in the gear forging after 500 pieces are shown at the tops of the data axes in Figure 43. These data and extrapolations support the die wear results recorded from previous series of gears in the die wear test.

6.0 FINISH MACHINING PHASE

The finish machining of final development forgings, produced from AMS 6265 steel, was performed to:

a. Demonstrate the capability of producing gears and pinions to drawing requirements, starting with integrally forged teeth.

b. Produce a quantity of finished gear sets suitable for functional and fatigue testing.

In this phase six sets of cut tooth gears, produced by standard methods, were also produced to serve as a test baseline. These cut gears were processed up to the heat treat operations and then the forged gears were heat treated and finished as a lot with six sets of baseline cut gears.

The pertinent machining operations, developed for the finishing of the forgings, are shown in the operation sketches, Figures 44 and 45 for the pinion and gear respectively. All other operations are standard production operations. The forged gears were subjected to some extra scrutiny for surface defects according to liquid penetrant inspection specification MIL-271C. The finished tooth contact patterns were all standard and are not reproduced in this report.

The gear is finish ground on the drive side and the coast side on the same pass, so separate values for the amount of stock removed could not be measured from the in-feed setting. However, the initial grinding contact pattern appeared fairly symmetrical so that approximately the same amount of stock was removed from all over the tooth form. The two sides of the pinion teeth are ground separately and therefore the stock removed can be measured independently.

Production inspection data was generated according to special procedures. The inspection data was organized to present the amount of finishing stock on the tooth flanks and on the root radii. These critical surfaces were left "as forged" for the carburizing and finishing operations. The equivalent cut gears accompanying the forged gears through these operations were measured in a similar manner for comparison and control purposes.

On examination of the Stock Removal Records and Table XIX indicates that the consistency of results, while not optimum, can be accommodated by the current processing operations. The operations will result in finished case depths within the drawing tolerance of .030" to .050" effective case depth or a total tolerance of .020" on the finished tooth. The stock removed in the root of the forged pinion teeth showed the broadest variation, with up to a maximum of .014" removed. This is still within the high side of the processing tolerance.

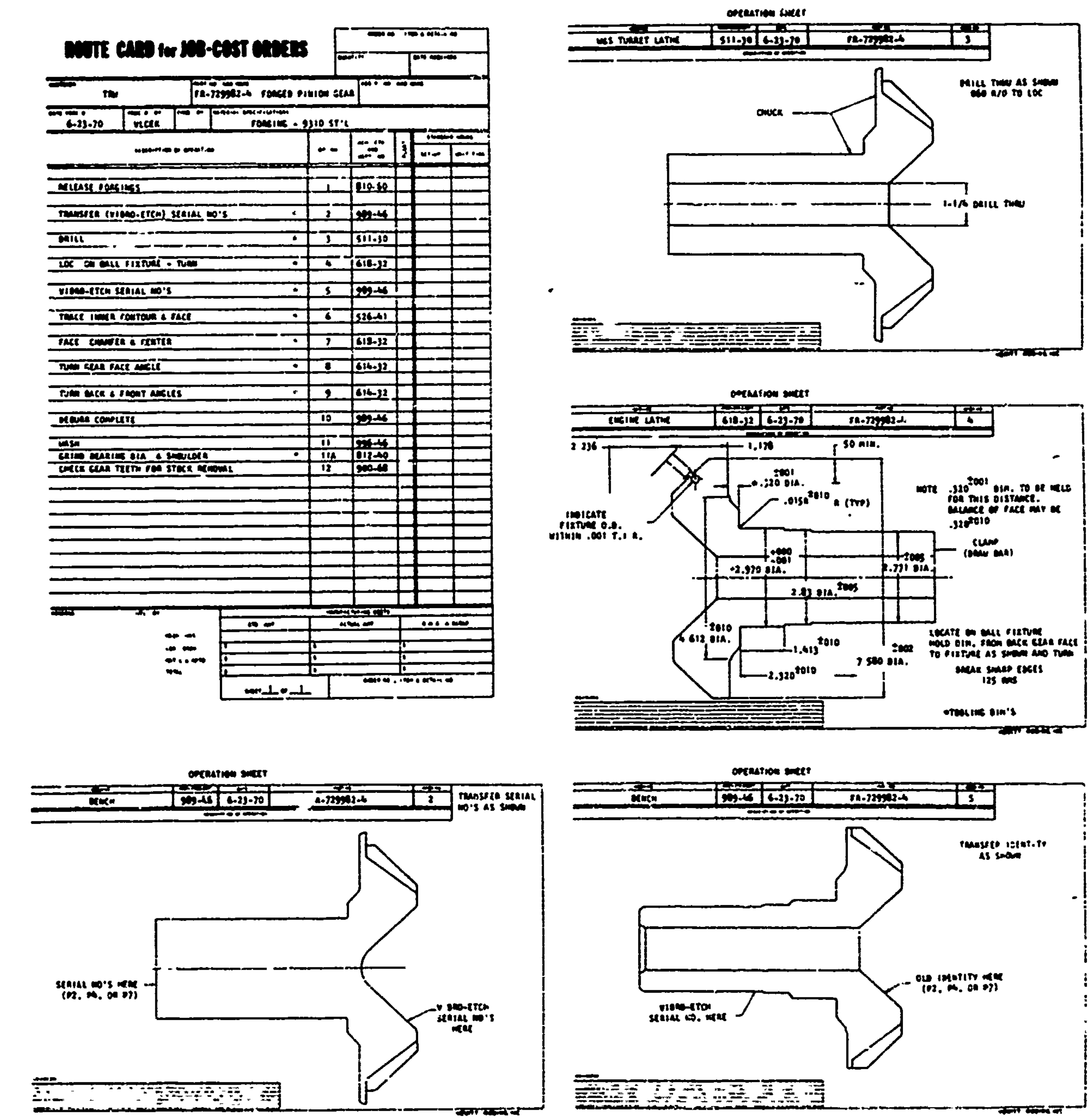


Figure 44. Pinion machining sequence sketches and layout.

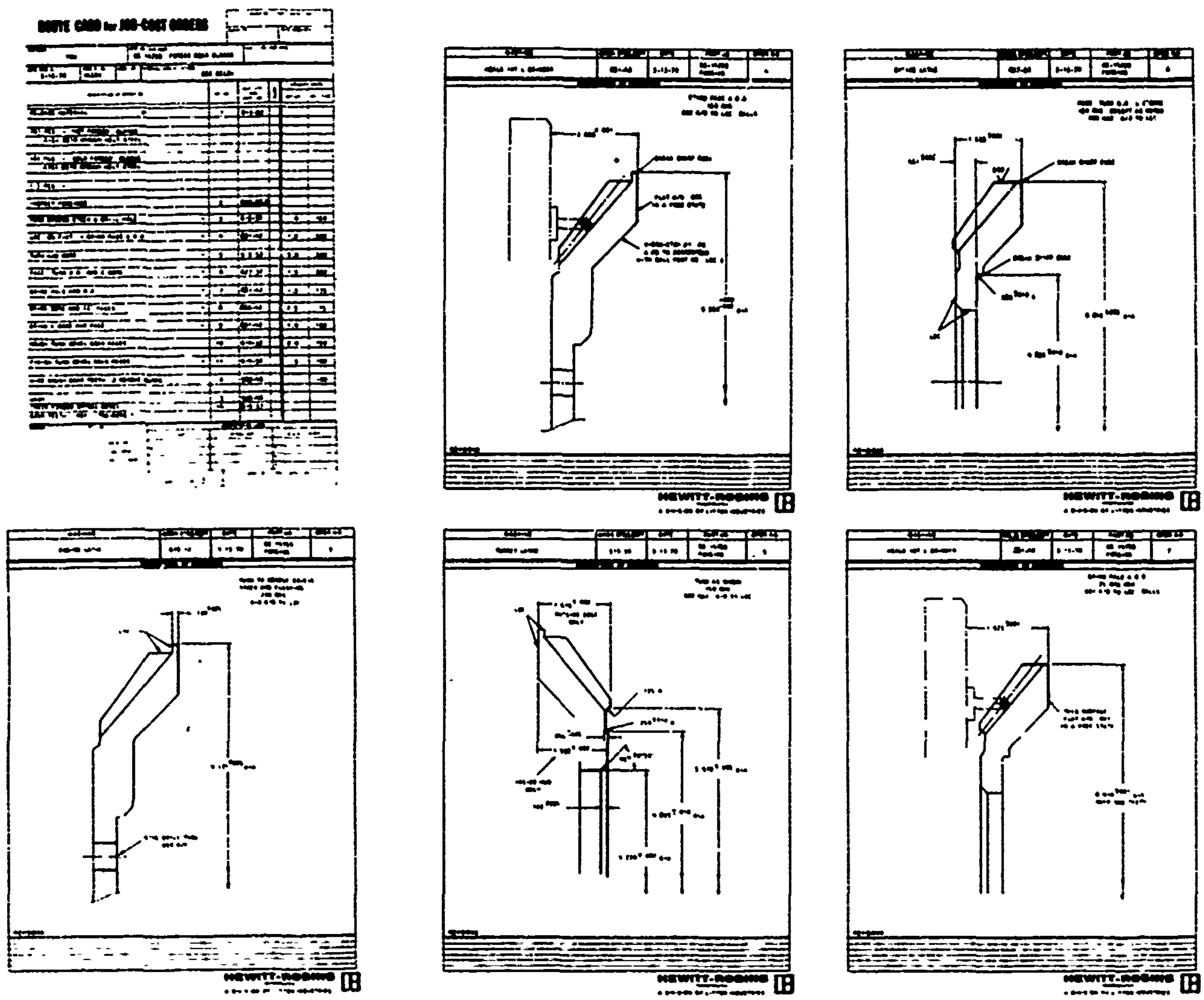
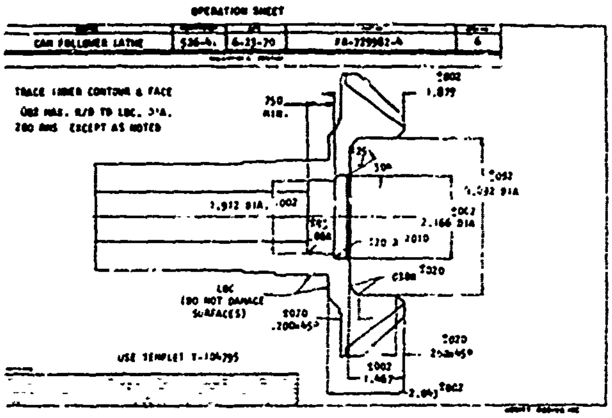
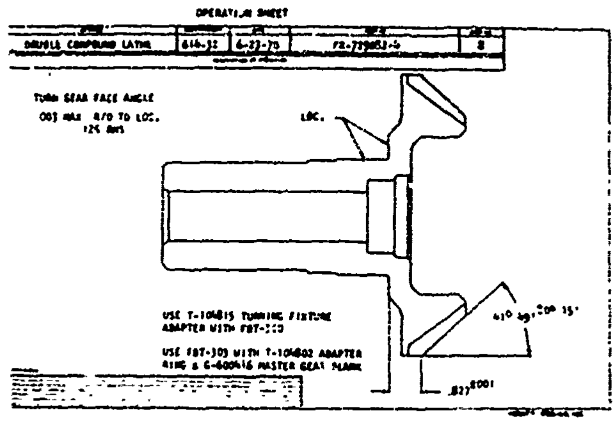
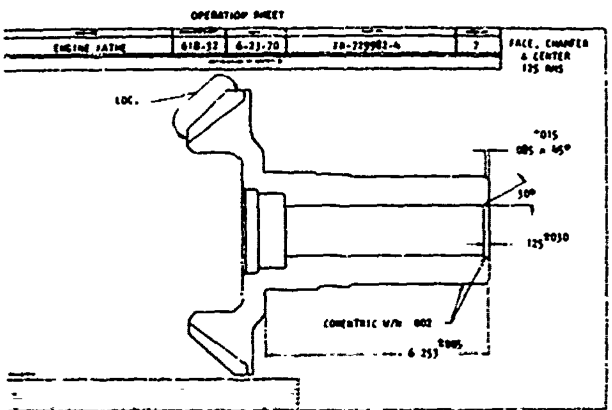
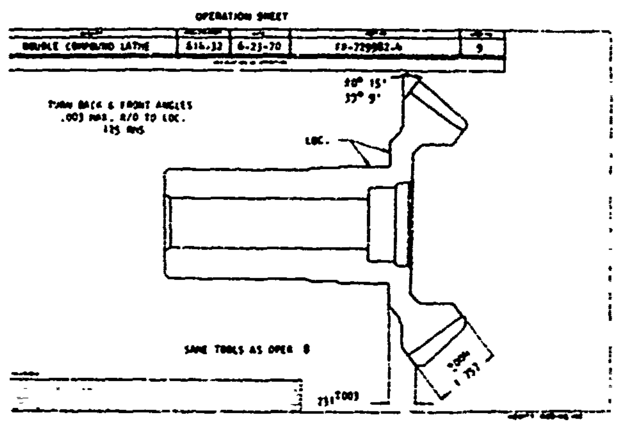


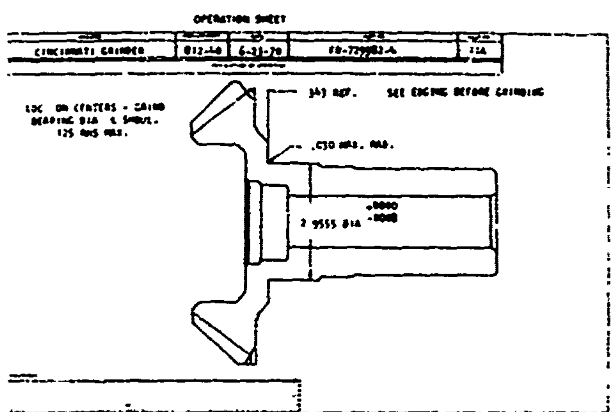
Figure 45. Gear machining sequence sketches and layout.


OPERATION SHEET
CAM FOLLOWER LATHE
6-23-70
USE TEMPLET T-104795


DOUBLE COMPOUND LATHE
6-23-70
TURN GEAR FACE ANGLE
LOC.


OPERATION SHEET
ENGINE LATHE
6-23-70
FACE, CHAMFER
& CENTER
125 RMS
LOC.
CONCENTRIC W/N .002


OPERATION SHEET
DOUBLE COMPOUND LATHE
6-23-70
TURN BACK & FRONT ANGLES
125 RMS
LOC.
SAME TOOLS AS OPER. 8

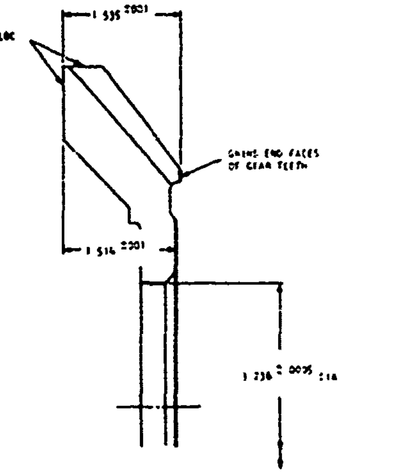

OPERATION SHEET
CINCINNATI GRINDER
6-23-70
SEE ENGINE BEFORE GRINDING

97 A

MACHINE	MACH CTR & DEPT	DATE	PART NO	OPER NO
BRYANT INT'L GRINDER	806-42	3-13-70	8E-14759 FORGING	8

DESCRIPTION OF OPERATION

GRIND BORE & (2) FACES
125 RMS MAX.
.001 MAX. R/O TO LOC.



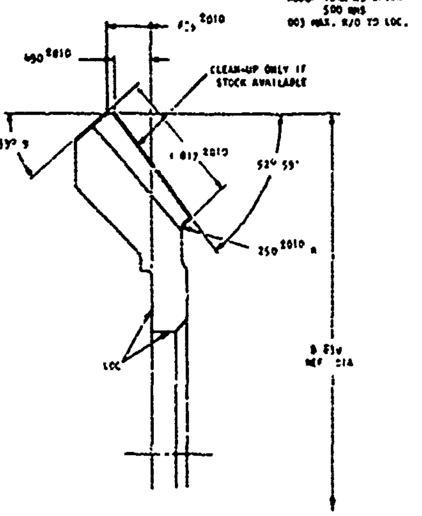
REVISIONS

HEWITT-ROBINS
A DIVISION OF LITTON INDUSTRIES

MACHINE	MACH CTR & DEPT	DATE	PART NO	OPER NO
DOUBLE COMPOUND LATHE	614-32	3-13-70	8E-14759 FORGING	10

DESCRIPTION OF OPERATION

ROUGH TURN AS SHOWN
500 RMS
.003 MAX. R/O TO LOC.



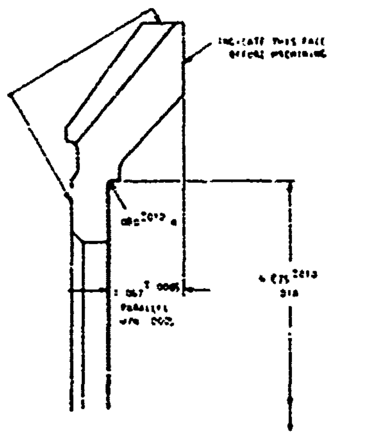
REVISIONS

HEWITT-ROBINS
A DIVISION OF LITTON INDUSTRIES

MACHINE	MACH CTR & DEPT	DATE	PART NO	OPER NO
HEALD INTERNAL GRINDER	881-42	3-13-70	8E-14759 FORGING	9

DESCRIPTION OF OPERATION

GRIND C'BORE & FACE
125 RMS MAX.
.002 MAX. R/O TO LOC.



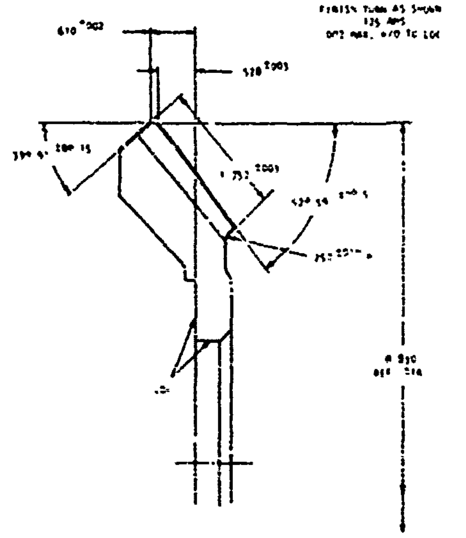
REVISIONS

HEWITT-ROBINS
A DIVISION OF LITTON INDUSTRIES

MACHINE	MACH CTR & DEPT	DATE	PART NO	OPER NO
DOUBLE COMPOUND LATHE	614-32	3-13-70	8E-14759 FORGING	[illegible]

DESCRIPTION OF OPERATION

FINISH TURN AS SHOWN
125 RMS
.002 MAX. R/O TO LOC



REVISIONS

HEWITT-ROBINS
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Table XIX

Range of Stock Removal

	Coast Side	Drive Side	Root
Cut Pinion	.007-.010"	.006-.010"	.005-.009"
Forged Pinion	.008-.013"	.005-.008"	.005-.014"
Cut Gear	.009-.011"		.010-.015"
Forged Gear	.008-.011"		.007-.014"

The results of these finishing operations, in terms of clean up stock, are consistent with the measurements taken on the unmachined forgings. This correlation serves to validate the forging inspection methods for spiral bevel gears developed on this program.

Two pinions, S/N 3PV18 and 3PV23, have visually observable pits on one or more teeth. The pitting has been attributed to excessive time in the nickel strip solution and is not the result of normal procedures.

The simplified inspection data are presented in the Stock Removal Tables XX through XXIII for cut gear, forged gear, cut pinion and forged pinion respectively. The observed ranges for the amount of finishing stock removed is shown in Table XIX. The optimum range is .007-.010" per surface.

STOCK REMOVAL RECORD #1

Part No. 114D-5245 Part Name Cut Gear Order L43564-01-0001

Ser. No.	Pitch Cone Reading (Tol. +.016/.026) Heel Diam. 1	Heel Diam. 2	Heel Diam. 3	Toe Diam. 1	Toe Diam. 2	Toe Diam. 3	Root Depth (Tol. .000/+.013) Heel 1	Heel 2	Heel 3	Toe 1	Toe 2	Toe 3	Stock Removal Side of Tooth C'st	Side of Tooth Dr'v	Loc	Root	Root Rad. Rough	Root Rad. Fin	Spacing T/T	Spacing Acc	RMS	B/L	Pattern
M-1183	.0275	.0275	.0275	.0215	.0215	.022	.012	.015	.013	.0055	.006	.006											
Mean		.0275			.0215				.013		.006			.009		.015							
ΔL			-.005						-.007														
M-1185	.028	.028	.0275	.020	.020	.0195	.012	.012	.012	.0055	.005	.0055											
Mean		.028			.020			.012		.0055				.010		.011							
ΔL			-.008						-.0065														
M-1186	.0275	.028	.0285	.0205	.021	.021	.0125	.0125	.0135	.0055	.0055	.006											
Mean		.028			.021			.0125			.0055			.0095		.012							
ΔL			-.007						-.007														
M-1190	.0275	.027	.0275	.021	.020	.021	.0125	.013	.0125	.0055	.006	.0055											
Mean			.0275	.021					.0125	.0055				.009		.0115							
ΔL			-.0065						-.0075														
M-1194	.0265	.0265	.0275	.020	.020	.0205	.0105	.0105	.011	.004	.004	.0055											
Mean		.0265			.020			.0105			.004			.0095		.012							
ΔL			-.006						-.0065														
M-1195	.026	.0285	.0285	.020	.022	.0225	.010	.0135	.013	.0045	.006	.007											
Mean		.028			.022				.012		.006			.0105		.0115							
ΔL			-.006						-.006														
M-1198	.0275	.0275	.028	.020	.020	.0205	.012	.012	.013	.005	.0055	.0065											
Mean		.028			.020			.012			.006			.0095		.0115							
ΔL			-.008						-.006														
M-1200	.0265	.0265	.0265	.019	.019	.019	.011	.0105	.010	.0045	.004	.005											
Mean		.0265			.019			.0105		.0045				.0095		.010							
ΔL			-.0075						-.0065														

Ball Size, Heel .312 Ball Size, Toe .242 Root Ga.____ Master Gear #106280

Root Size Set .003" Shallow Both Heel & Toe

Table XX

STOCK REMOVAL RECORD #1

Part No. 1140-5245 Part Name Cut Gear Order L43564-01-0001

Ser. No.	Pitch Cone Reading (Tol. +.016/.026)						Root Depth (Tol. .000/+.013)						Stock Removal				Root Rad		Spacing		RMS	B/L	Pattern
	Heel Diam.			Toe Diam.			Heel			Toe			Side of Tooth		Loc	Root	Rough	Fin	T/T	Acc			
	1	2	3	1	2	3	1	2	3	1	2	3	C'st	Dr'v									
M-1203	.028	.0285	.0285	.021	.021	.0215	.0145	.014	.013	.007	.0075	.007											
Mean		.0285			.021			.014		.007				.009		.0135							
Δ			-.0075						-.007														

Table XX (continued)

Page 1 of 2

STOCK REMOVAL RECORD #2

Part No. SK 22270 Part Name Forged Gear Order L43564-0-0001

Ser. No.	Pitch Cone Reading (Tol. +.016/.026) Heel Diam. 1	Heel Diam. 2	Heel Diam. 3	Toe Diam. 1	Toe Diam. 2	Toe Diam. 3	Root Depth (Tol. .000/+.013) Heel 1	Heel 2	Heel 3	Toe 1	Toe 2	Toe 3	Stock Removal Side of Tooth C'st	Side of Tooth Dr'v	Loc	Root	Root Rad. Rough	Root Rad. Fin	Spacing T/T	Spacing Acc	RMS	B/L	Pattern
4V4	.021	.0235	.019	.0245	.025	.025	.003	.0045	.001	.0065	.007	.006											
Mean	.021				.025		.003			.0065				.009		.0095							
Δℓ			+.004						+.0035														
4V5	.023	.022	.021	.026	.025	.0255	.001	.0025	.001	.009	.008	.007											
Mean		.022				.0255			.0015		.008			.008		.014							
Δℓ			.0035						+.0065														
4V16	.0255	.0265	.026	.0255	.0265	.0255	.006	.006	.005	.0055	.0055	.005											
Mean			.026	.0255				.006			.0055			.009		.006							
Δℓ			-.0005						-.0005														
4V17	.0245	.0255	.026	.024	.0245	.0245	.004	.006	.005	.0065	.0065	.0065											
Mean		.0255			.0245				.005		.0065			.0095		.008							
Δℓ			-.001						+.0015														
4V18	.024	.025	.025	.024	.024	.023	.003	.0045	.005	.0055	.0055	.006											
Mean		.025			.024			.004			.0055			.0085		.008							
Δℓ			-.001						+.0015														
4V19	.027	.0255	.026	.025	.023	.024	.0035	.005	.004	.0055	.0055	.0055											
Mean			.026			.024			.004		.0055			.0105		.011							
Δℓ			-.002						.0015														
4V20	.024	.024	.026	.025	.023	.024	.001	.0025	.0045	.005	.0055	.007											
Mean		.025				.024		.003			.006			.0085		.009							
Δℓ			.001						+.003														
4V21	.023	.024	.024	.024	.023	.023	.002	.0055	.004	.006	.006	.006											
Mean			.0245		.023				.004		.00[illegible]			.008		.0065							
Δℓ			-.0015						+.002														

Ball Size, Heel .312 Ball Size, Toe .242 Root Ga ________ Master Gear #106280

Root Size Set .003" Shallow Both Heel & Toe

Table XXI

STOCK REMOVAL RECORD #2

Part No. SK 22270   Part Name Forged Gear   Order L43564-0-0001

Ser. No.	Pitch Cone Reading (Tol. + .016/.026)						Root Depth (Tol. .000/+.013)						Stock Removal				Root Rad.		Spacing		RMS	B/L	Pattern
	Heel Diam.			Toe Diam.			Heel			Toe			Side of Tooth		Loc	Root	Rough	Fin	T/T	Acc			
	1	2	3	1	2	3	1	2	3	1	2	3	C'st	Dr'v									
4V22	.025	.0245	.0245	.023	.022	.022	.003	.0025	.001	.004	.0035	.0035											
Mean		.0245			.022			.002			.0035			.0105		.0135							
ΔL			-.0025						+.0015														
4V23	.0245	.024	.0245	.024	.024	.024	.004	.004	.004	.007	.006	.007											
Mean			.0245		.024			.004		.007				.008		.007							
ΔL			.0005						+.003														
4V24	.025	.026	.0265	.023	.023	.022	.0035	.0045	.004	.005	.0045	.004											
Mean		.026			.023				.004		.0045			.0095		.0075							
ΔL			-.003						+.0005														
4V25	.0245	.026	.0265	.0245	.0245	.024	.002	.005	.005	.005	.007	.006											
Mean		.0255			.0245			.004				.006		.009		.007							
ΔL			-.001					+.002															

Table XXI (continued)

STOCK REMOVAL RECORD #3

Part No. 114D 6244 Part Name Cut Pinion Order L43562-01-0001

Ser. No.	Pitch Cone Reading (Tol. +.016/.026) Heel Diam. 1	Heel Diam. 2	Heel Diam. 3	Toe Diam. 1	Toe Diam. 2	Toe Diam. 3	Root Depth (Tol. .000/+.013) Heel 1	Heel 2	Heel 3	Toe 1	Toe 2	Toe 3	Stock Removal Side of Tooth C'st	Side of Tooth Dr'v	Loc	Root	Root Rad Rough	Root Rad Fin	Spacing T/T	Spacing Acc	RMS	B/L	Pattern
1050	.022	.023	.023	.022	.024	.022	.007	.008	.008	.010	.010	.011											
Mean			.023		.023			.008			.010		.009	.010		.005/							
Δℓ			+.000							+.002						.006							
1064	.022	.023	.023	.022	.022	.021	.006	.007	.006	.01?	.010	.0105											
Mean	.022				.022		.006					.0105	.007	.007		.009/							
Δℓ			.000						.0045							.009							
1068	.020	.020	.021	.020	.022	.022	.004	.003	.002	.008	.010	.009											
Mean		.020			.022			.003				.009	.006	.006		.009/							
Δℓ			+.002						+.006							.008							
1113	.022	.023	.021	.022	.022	.0205	.008	.007	.006	.011	.011	.011											
Mean	.022				.022			.007			.011		.009	.009		.008							
Δℓ			.000							.005													
1114	.021	.020	.021	.021	.0225	.020	.006	.004	.004	.0115	.012	.011											
Mean			.021	.021				.005		.0115			.009	.010		.006/							
Δℓ			.000						+.0075							.009							
1115	.022	.023	.023	.0205	.0205	.022	.007	.009	.010	.006	.006	.007											
Mean			.023		.021			.009			.006		.007	.009		.006/							
Δℓ				-.002					-.003							.007							
1116	.025	.025	.023	.022	.021	.022	.010	.0105	.0105	.012	.011	.012											
Mean		.024		.022				.0105		.012			.009	.006		.006/							
Δℓ			.002						+.0015							.006							
1117	.024	.023	.023	.021	.022	.020	.010	.007	.010	.009	.009	.007											
Mean		.023		.021				.009			.008		.009	.009		.005/							
Δℓ			-.002							-.001						.006							

Ball Diam, Heel .344 Ball Diam, Toe .2185 Root Ga______ Master Gear 106352

Table XXII

STOCK REMOVAL RECORD #3

Part No. 1140 6244 Part Name Cut Pinion Order No. L43562-01-0001

Ser. No.	Pitch Cone Reading (Tol. +.016/.026)						Root Depth (Tol. .000/+.013)						Stock Removal				Root Rad.		Spacing		RMS	B/L	Pattern
	Heel Diam.			Toe Diam.			Heel			Toe			Side of Tooth		Loc	Root	Rough	Fin	T/T	Acc			
	1	2	3	1	2	3	1	2	3	1	2	3	C'st	Dr'v									
1119	.022	.021	.020	.020	.019	.019	.005	.0065	.006	.010	.0115	.011											
Mean		.021			.019				.006			.011	.010	.006		.005/.006							
Δ∠			-.002						+.005														
1120	.020	.020	.020	.019	.018	.020	.004	.004	.005	.012	.012	.011											
Mean		.020		.019				.004		.012			.010	.008		.005/.006							
Δ∠			-.001						+.008														

Table XXII (continued)

STOCK REMOVAL RECORD #4

Part No. SK22269 Part Name Forged Pinion Order No. L43562-01-0001

Ser. No.	Pitch Cone Reading (Tol. +.016/.026)						Root Depth (Tol. .000/+.013)						Stock Removal				Root Rad.		Spacing				
	Heel Diam.			Toe Diam.			Heel			Toe			Side of Tooth		Loc	Root	Rough	Fin	T/T	Acc	RMS	B/L	Pattern
	1	2	3	1	2	3	1	2	3	1	2	3	C'st	Dr'v									
3PV3	.019	.020	.022	.023	.024	.024	.002	.0025	.003	.0085	.008	.0095											
Mean		.020			.024			.0025		.0085			.008	.008		.008/.010							
ΔL		+.004							+.006														
3PV4	.025	.028	.028	.029	.030	.030	.012	.014	.013	.008	.010	.008											
Mean		.028			.030				.013	.008			.012	.005		.012/.011							
ΔL		+.002							-.005														
3PV16	.020	.0205	.022	.022	.0225	.024	.013	.011	.009	.0105	.0135	.013											
Mean		.021			.023			.011				.013	.010	.007		.005/.006							
ΔL		+.002								+.002													
3PV17	.022	.022	.021	.023	.022	.025	.0035	.005	.006	.012	.012	.0115											
Mean		.022			.022			.005			.012		.012	.007		.005/.006							
ΔL			.000						+.007														
3PV18	.023	.015	.023	.024	.021	.0215	.0055	.0035	.008	.012	.0115	.0115											
Mean		.020			.022			.006			.0115		.013	.008		.006/.006							
ΔL			+.002							+.0055													
3PV19	.021	.018	.023	.023	.023	.025	.007	.008	.011	.012	.012	.014											
Mean	.021				.023			.009			.013		.008	.008		.010/.014							
ΔL			+.002							+.004													
3PV20	.022	.020	.026	.028	.024	.028	.011	.010	.011	.016	.013	.017											
Mean		.023			.027		.011				.015		.013	.007		.012/.011							
ΔL			+.004						+.004														
3PV21	.019	.019	.020	.019	.019	.020	.005	.004	.006	.006	.006	.008											
Mean		.019			.019		.005			.006			.008	.006		.010/.010							
ΔL			.000						-.001														

Ball Diam, Heel .344" Ball Diam, Toe .2185" Root Ga ______ Master Gear 106352

Table XXIII

STOCK REMOVAL RECORD #4

Part No. SK22269 Part Name Forged Pinion Order NO. L43562-01-0001

Scr. No.	Pitch Cone Reading (Tol. +.016/.026) Heel Diam. 1	Heel Diam. 2	Heel Diam. 3	Toe Diam. 1	Toe Diam. 2	Toe Diam. 3	Root Depth (Tol. .000/+.013) Heel 1	Heel 2	Heel 3	Toe 1	Toe 2	Toe 3	Stock Removal Side of Tooth C'st	Side of Tooth Dr'v	Loc	Root	Root Rad. Rough	Root Rad. Fin	Spacing T/T	Spacing Acc	RMS	B/L	Pattern
3PV22	.022	.02:	.022	.023	.023	.024	.007	.0085	.0085	.010	.0085	.011											
Mean			.022		.023			.0085		.010			.010	.007		.005/.007							
ΔL			+.001						+.0015														
3PV23	.022	.0235	.023	.0235	.025	.026	.010	.010	.006	.010	.014	.012											
Mean			.023		.025			.009				.012	.012	.008		.010/.009							
ΔL			+.002						+	.003													
3PV24	.022	.022	.018	.024	.023	.022	.005	.005	.004	.013	.010	.013											
Mean		.021			.023			.005		.012			.013	.008		.007/.008							
ΔL			+	.002					+.00	7													
3PV25	.022	.0205	.0225	.022	.0215	.022	.006	.006	.008	.009	.010	.009											
Mean	.022			.022				.007		.009			.009	.008		.007/.007							
ΔL			-.001						+.002														

Table XXIII (continued)

7.0 MECHANICAL TESTS AND METALLURGICAL EVALUATION

7.1 Mechanical Tests

A program of testing was performed to evaluate the mechanical properties of forged gears and to compare these properties with those obtained in conventional cut gears of the same configuration, material and heat treatment. The main variable in this comparison, therefore, was the forging versus machining method of obtaining the tooth configuration. Precautions were taken to minimize the influence of uncontrolled variables in the test gears. Both types of test gears were made from the same AMS 6265 steel and were heat treated and finish machined together as a group according to the specification in Boeing Drawing No. 114-D-6244 and 114-D-6245.

Mechanical testing consisted of a comparative single tooth fatigue evaluation under unidirectional loading conditions. Although this type of test does not strictly simulate the conditions of loading experienced in service, the test is a meaningful one for comparative purposes because the condition of loading can be duplicated and because the test measures fatigue life which is considered to be an important mechanical property parameter in gear design. In this type of test the general mode of loading is similar to the loading experienced in service but the rate of loading is less rapid and the load is applied to a greater portion of the tooth within a given time increment (7).

The single tooth fatigue testing of spiral bevel gears is a relatively difficult mechanical problem and has not been previously reported in the published test literature. The procedures developed on this program represent an advance in the state-of-the-art techniques. The single tooth loading requirement necessitated the design and assembly of a test system to permit the conduct of the testing under consistent, reproducible conditions. This was accomplished through the system shown in Figure 46.

The loading arrangement, shown in close-up in Figure 47, utilized a standard pinion to provide the load to the gear teeth. A schematic of the pinion loading arrangement is also shown in Figure 48.

The integral shaft of the pinion was first removed and the back of the pinion was ground flush to permit direct contact to the bearing mounted pinion shaft. This shaft was mounted on preloaded roller thrust bearings so that the longitudinal motion of the shaft was minimized and would not influence test results. A series of holes for dowel pins was machined into the pinion to permit direct mounting of the pinion to the loading ring. The pinion was finally secured by the locknut on the end of the pinion shaft of the fixture. The slotted countersunk holes on the loading ring permitted changing of the gear-contact pinion tooth without removal of the pinion from the shaft.

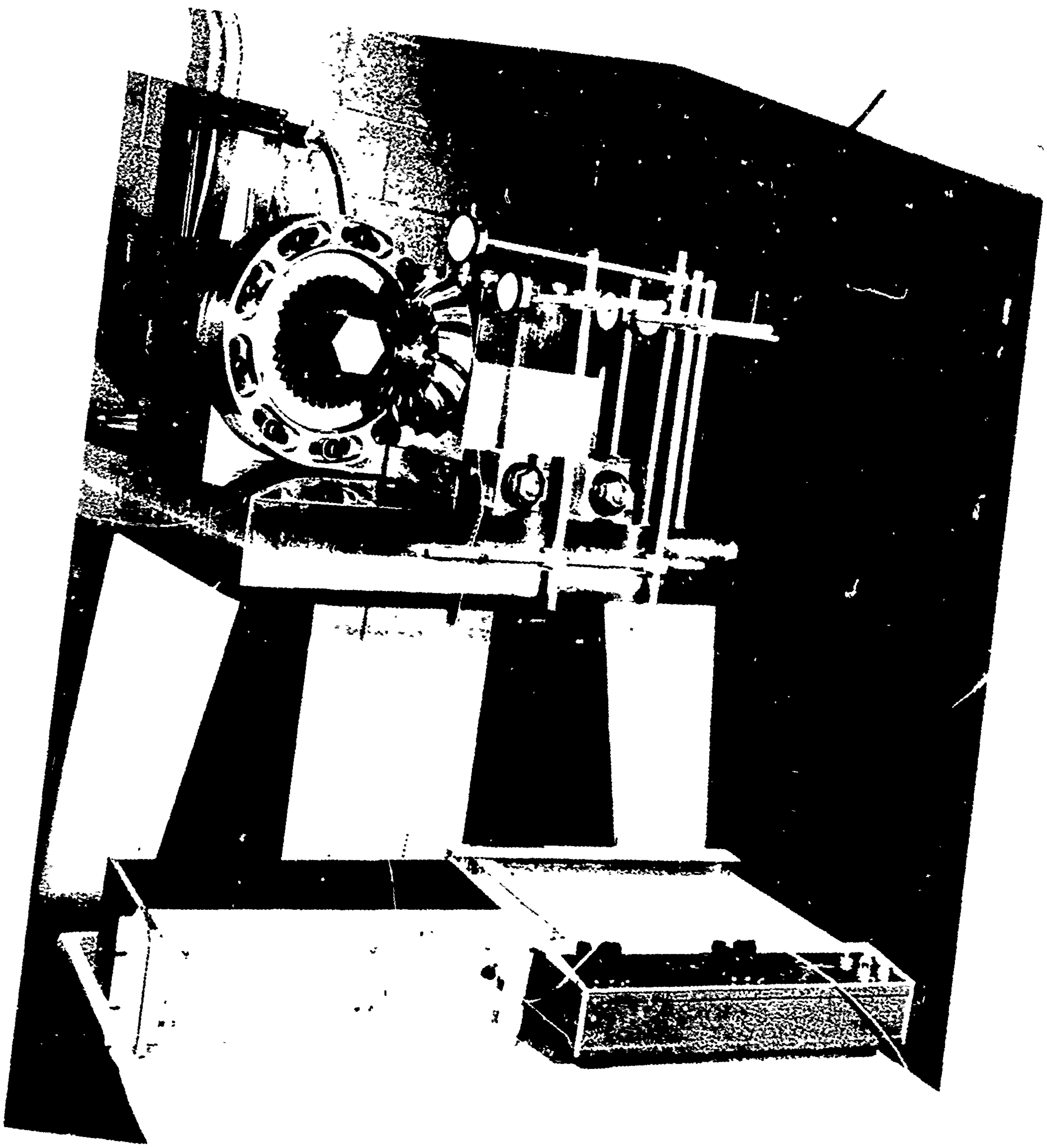
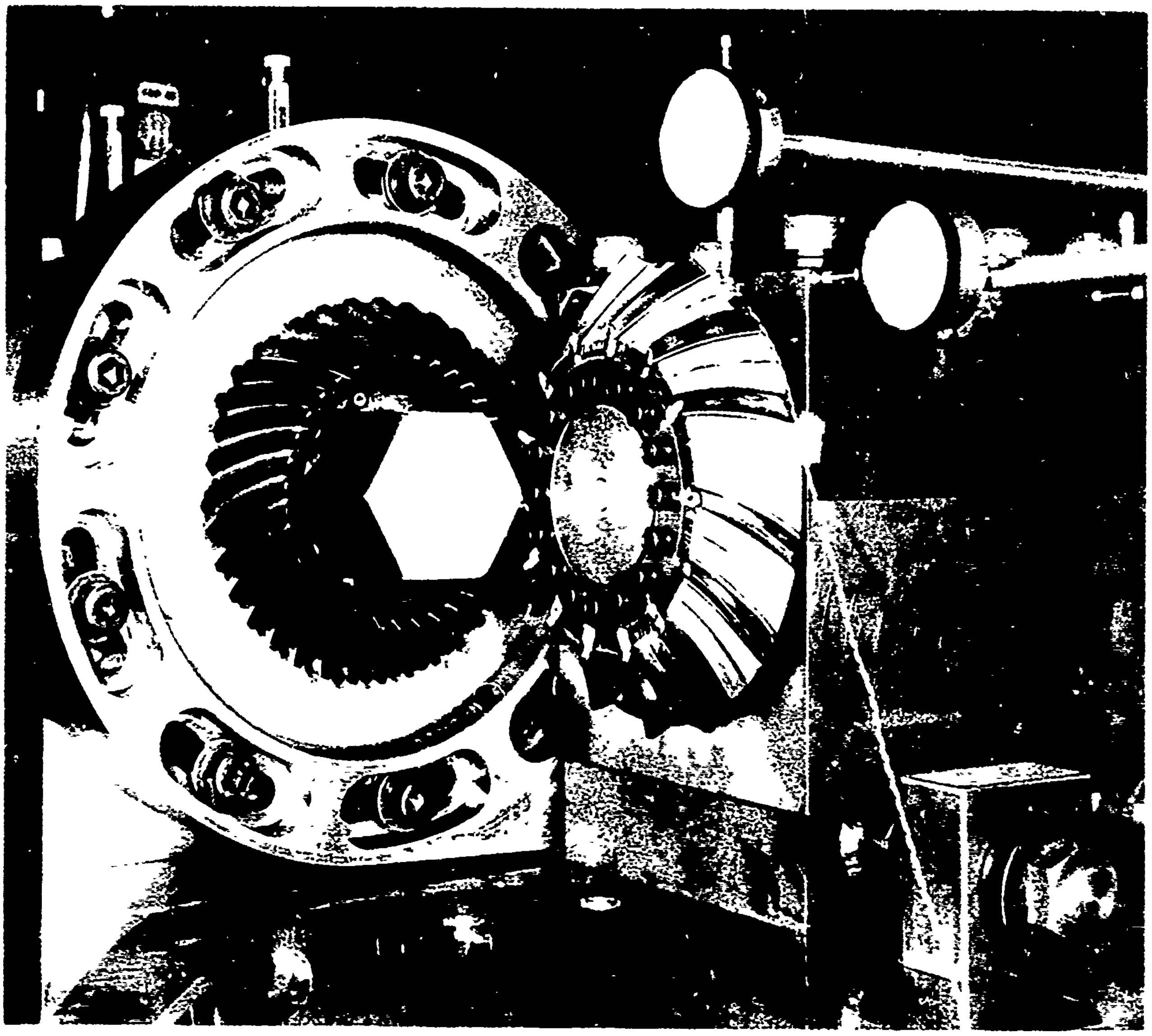


Figure 46. Fatique test set-up.



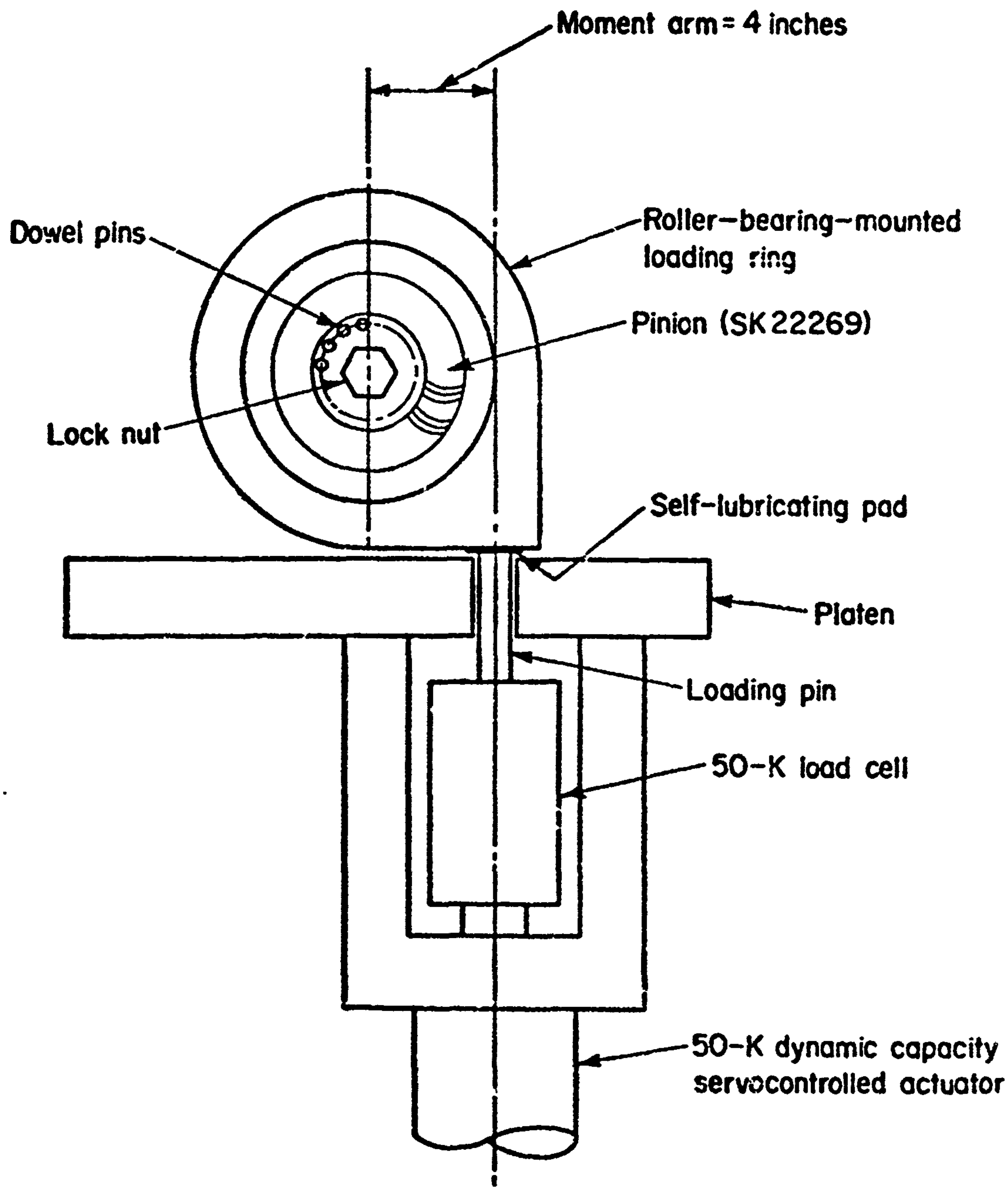


Figure 48. Schematic of pinion loading arrangement.

The force of the loading ring was supplied by a 50-kip-capacity electrohydraulic servocontrolled actuator mounted under the platen of the test system. (The actuator is not visible in Figures 46 or 47, but is shown in the schematic of Figure 48.) A 50-kip-capacity load cell was mounted in series with the actuator to provide the feedback for the closed-loop control of each test. A loading pin, in bearing against a self-lubricating oil-impregnated bronze pad, completed the load string to the pinion. The actuator load was applied off-center with respect to the shaft, resulting in a moment arm of four inches. Hence, the torque transmitted by the pinion was the actuator load times four inches. The actual load applied by the pinion tooth to gear teeth was 33% greater than the actuator force due to the shorter moment arm from the pinion center to the pinion tooth contact area.

The technique used to mount the test gear is partially visible in Figure 47. Prior to mounting the gear on the fixture, every second and third tooth was carefully removed (by grinding) to provide a single exposed tooth to carry the load transmitted by the pinion tooth. The test gear was then bolted to the gear shaft which, in turn, was clamped into place in the split housing block. An important feature of this fixture is the capability to reproduce accurately the test conditions to minimize variability attributable to the set up. Care was taken in setting up the installation and in the alignment procedures for each tooth. The detailed procedure is discussed in the following paragraphs.

With a gear and pinion installed in accordance with the dimensions on the drawings for each part, the alignment was adjusted to produce an initial static bearing pattern falling on a diagonal line from the heel at the top land and toe at the base as shown in Figure 49. The bearing housing was then lowered in order to shift the line of load application approximately 1/32" toward the outer edge of the gear (see Figure 49). At the same time, care was taken to prevent the contact pattern from running out at either of the tooth edges. This shift in pattern also attempted to bias the loading on the gear teeth (as compared with the pinion tooth) to minimize pinion tooth failures. The final bearing pattern was approximately 1.0" in length, starting 1/2" from the heel and ending 7/32" from the toe under 10,000 pounds actuator load or 13,330 pounds on the tooth.

After the fixtures were aligned in the above manner, additional checks were made to insure reproducibility of the bearing pattern. It was then only necessary to rotate the gear shaft and lock it in a position so that a common reference point could be located in each tooth. This was accomplished using a micrometer height gage set to a precise height (7.005") from the fixture platen to the base of the toe of each tooth.

As an additional check of the fixturing, five dial gages were mounted from the platen to check the rigidity of the fixed gear block. Deflections were then read under an applied load. As shown in the results (Table XXIV), there does not appear to be any consistent relationship between the applied load and the deflection at any of the dial gage locations. In view of the indicated rigidity, no further measurements of this type were made.

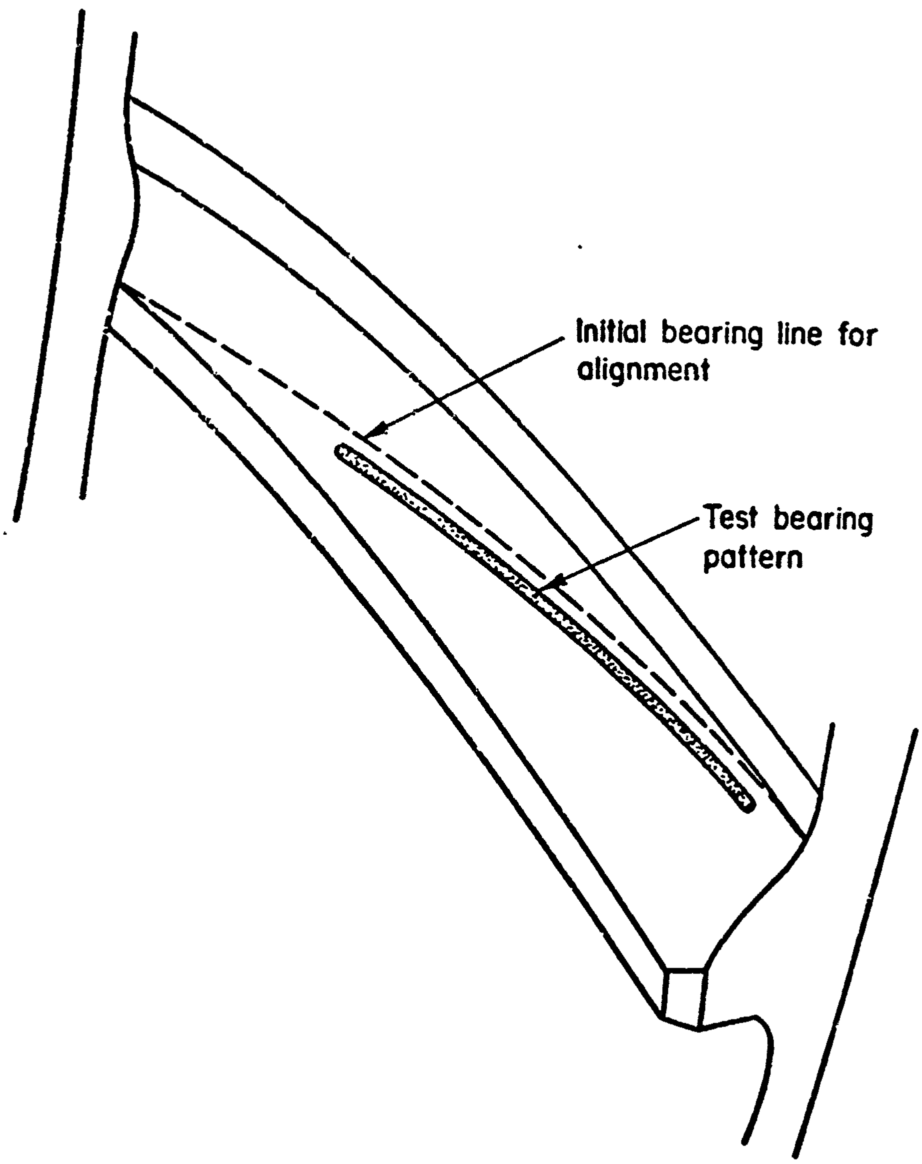
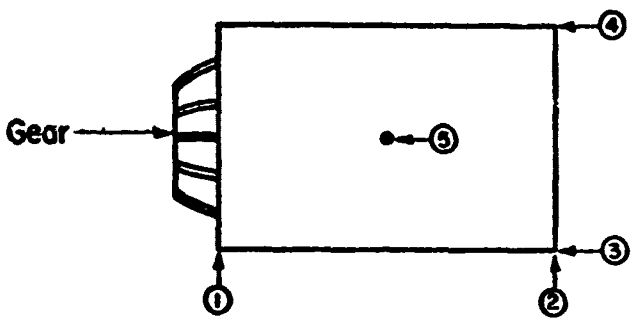


Figure 49. Bearing pattern of gear teeth.

Table XXIV

Results of Fixture Deflection Movements



TOP VIEW OF GEAR FIXTURE HOUSING
SHOWING DIAL GAGE LOCATIONS

Gear Number	Tooth Number	Applied Load, Pounds*	Indicated Deflections, Inches 1	2	3	4	5
M1200	4	25,740	.00075	0	.00075	0	0
	5	25,740	.0010	.00025	.0010	.0010	.00025
	6	30,000	.0005	.00025	.0005	.00025	0
	7	30,000	.0005	0	.0005	0	0
	8	30,000	0	.001	.0005	.0003	0
	9	20,000	.00075	0	.0005	.00025	0
	10	20,000	.001	0	0	.00025	0
	12	30,000	.002	0	0	.00075	0

*Moment arm = 4 inches.

Prior to the initiation of the fatigue evaluations, the use of the AGMA formula for the prediction of maximum gear tooth bending stress was investigated. Based upon Equation (1) of the referenced standard (8), the bending stress is given by the equation

$$S_t = \frac{W_t K_o P_d K_s K_m}{K_v F J}$$

where S_t = calculated tensile stress at the root of the tooth, psi

W_t = transmitted tangential load at large end pitch diameter, pounds ($W_t = \frac{2T}{d}$) T = pinion torque in pound-inches; d = large end pitch diameter

K_o = overload factor (assumed = 1)

K_v = dynamic factor (assumed = 1)

P_d = diametral pitch at large end of the tooth = 4.93"

F = face width, inches = 1.75"

K_s = size factor = 0.67 (from Figure 2 of reference)

K_m = load distribution factor (assumed = 1)

J = geometry factor = 0.295 (from Figure 4 of reference)

In order to approximate a tooth bending stress, it was necessary to assume values for the various factors entering into the solution of this equation. The tables and graphs in the AGMA standard are essentially based upon spiral gears with 20-degree pressure angle, 35-degree spiral angle and 90-degree shaft angle. Therefore, it is important to note that the application of this formula to the pinion and gears of this program does have some limitations and inherent inaccuracies.

Nevertheless, with the assumed factors substituted into the formula, the bending stress was computed to be

$$S_t = 7.24 \text{ P}$$

where P = applied actuator load, pounds. It should be noted that this predicts a linear relationship between the applied load and bending stress.

In order to determine more accurately the bending strains in a gear tooth fillet, 20 gear teeth were instrumented with 15 mil gage length electrical resistance strain gages (micromeasurements EA-06-015EH-120 gages). The first of these instrumented teeth had gages at the 1/4, 1/2, and 3/4 points along the tooth length as close as possible to the point of tangency of the tooth and fillet. The tooth was then incrementally loaded. The maximum fillet strain was observed near the center of the gear tooth. It was also noted that the strain distribution shifted from the heel toward the toe as the load increased.

All other gear teeth were instrumented with only one gage at the center of the tooth. The leads from this gage were wired into a strain gage input module (Daytronics) and balanced. This output and the load output from the control console were then connected to an X-Y recorder to give a continuous load-strain recording as the tooth was loaded. The specimen was then cycled twice to the peak load for that particular test.

The results of the strain gage experiments indicated, first of all, nonlinear behavior (between load and strain). Also, the loading and unloading curves, as well as the first and second cycle curves, were slightly offset, sometimes over several hundred microinches. This also resulted in very much scatter and not much reproducibility from tooth to tooth. Some of this can be attributed to minor variations in gage locations, tooth-to-tooth variations, and possible tooth-to-tooth geometry or tolerance variations. The difference between the first and second cycles may be related to friction forces, for several curves did indicate some discontinuities in the curves.

In attempting to reduce the data to a presentable format, the loading and unloading curves for each of the two cycles for each tooth were first averaged. The two curves for 15 specimens (30 curves) were then further averaged to arrive at the plot of strain versus actuator load shown in Figure 50. From the standard deviations shown, it can be noted that the scatter is indeed high. If the hysteresis were also taken into account, the standard deviation would be reduced several hundred microinches.

The nonlinear general relationship between strain and actuator load is typical of all recorded curves. This can be attributed to the initial seating of the gear and pinion teeth and the later shifting of the point of maximum stress as the load is increased .

Based upon a modulus of 30×10^6 psi, the average maximum stress at a peak torque of 120,000 pound inches (30,000 pounds actuator load times the 4" moment arm) was approximately 146,000 psi. This stress can be compared to 217,000 psi predicted by the AGMA formula (with the cautions previously discussed) After completion of the strain gage runs, the fatigue evaluation for that tooth was then initiated.

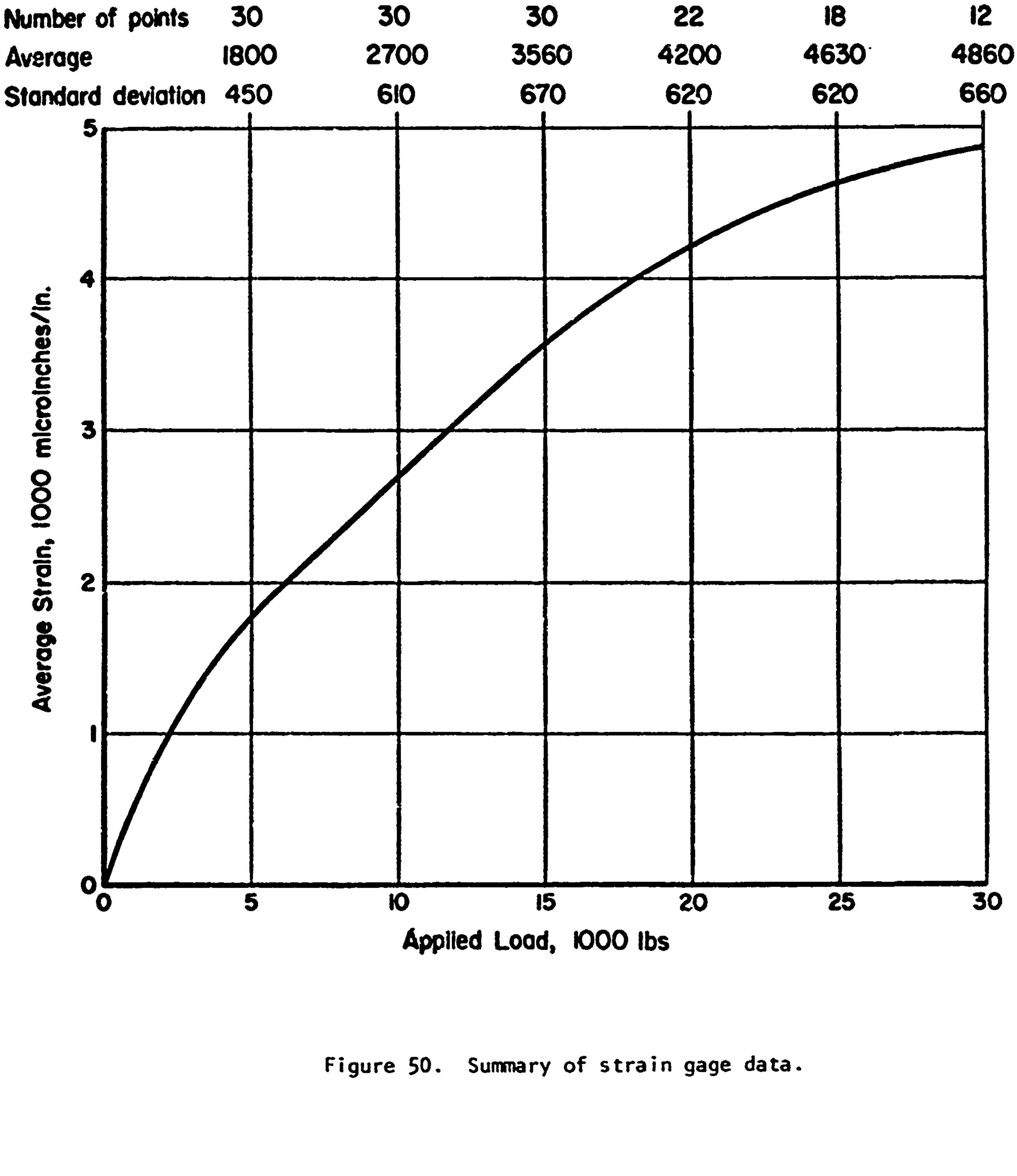


Figure 50. Summary of strain gage data.

All fatigue evaluations were conducted at R = 0 (minimum load = 0). The cyclic frequency for each test depended upon the maximum applied load and varied between 10 and 20 Hz. The fatigue test results are presented graphically in Figure 51. It should be noted once more that the loads shown on the graph are the applied actuator loads. (The tooth loads are approximately 33 percent greater than the actuator loads.)

An attempt was made to analyze the data using an available fatigue analysis program, but the scatter prevented an accurate analysis. In reviewing the data shown in Figure 51, it appears that the endurance limit of the forged gears is significantly higher than that of the cut gears as indicated by the results at the 15,000 pound load level. Three of the four forged gear tests at this level did not fail above 4.6 million cycles whereas the three cut gear tests all failed below 300,000 cycles. Results at the higher load levels did not indicate a significant difference between forged and cut gears, if anything the cut gears fared somewhat better. The greater importance of the results at the load levels near the design point becomes apparent when considering the magnitude of the design torque relative to the torques applied at the various test levels. The design torque per tooth is approximately 16,000 inch-lbs at maximum HP whereas the torque applied at the lowest test load level is 60,000 inch-lbs per tooth.

The large amount of scatter which is typical of gear tooth fatigue tests prevented a precise endurance limit determination with the limited number of tests allotted. Any future tests to supplement the data in Figure 51 should be concentrated at the lower load levels, decreasing from the 15,000 to 20,000 pound load level. To quantitatively assess the difference in fatigue properties between cut and forged gears it would be most informative to determine the difference in the endurance limit between them because design calculations are based on this parameter.

7.2 Metallurgical Evaluation

The objective of this evaluation was to compare the metallurgical features of the cut versus forged tooth test gears to verify the adequacy and similarity of heat treatment among test gears and to evaluate any differences in structure which may be present as a result of the cutting versus forging operations. The analysis consisted of case depth measurement, general structure evaluation and observations of the location and mode of fatigue fractures. These analyses are presented separately below.

7.2.1 Case Depth

The carburized case depth and hardness requirements after finish machining as specified in Boeing Drawing 114-D-6245, are tabulated below:

Carburize process specification: Boeing MS 12.02

Carburized case hardness: Rc 59-64

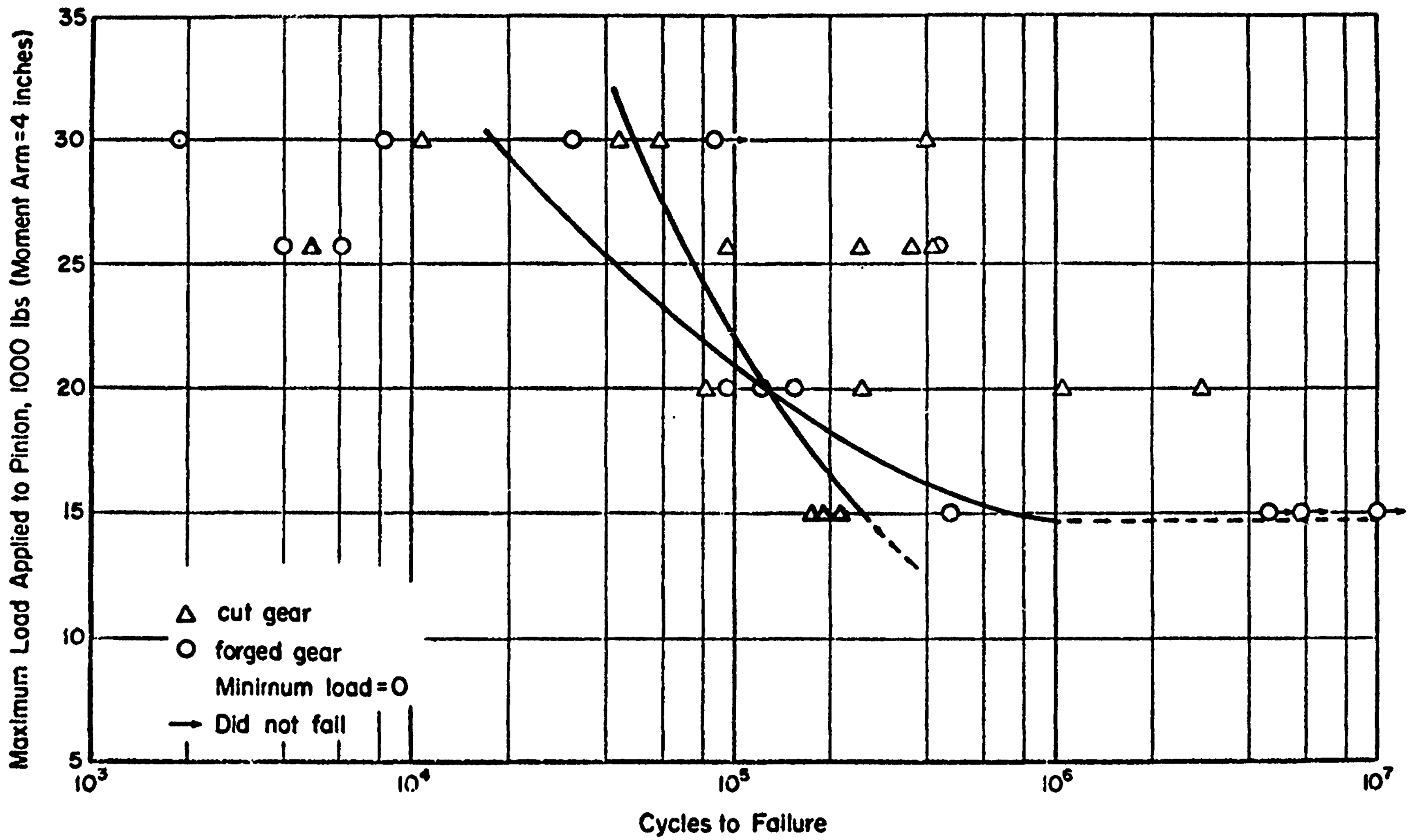


Figure 51. Fatigue test results for cut and forged gear teeth.

Effective case depth after grinding: .030-.050"

Core Hardness (Rc): 32-42

The test gears used for this evaluation were made from the AMS 6265 steel and all were heat treated as a lot to ensure uniformity. The only obvious variable which would result in case depth differences among the final finished gears is the amount of grinding required after carburizing to obtain the final configuration.

Case depth measurements were made by taking microhardness profiles near the surface of cut and forged gears and pinions. Hardness readings were made on sectional tooth profile surfaces perpendicular to the tooth centerline and midway between the heel and toe. A 100 gram miniload was used with a Knoop indenter to obtain hardness readings in the surface layer of the gear to a depth of approximately 0.070". The results of these hardness readings for both forged and cut gears and pinions are plotted in Figures 52 and 53. These graphs indicate that the case depths in both cut and forged test gears and pinions were somewhat below specification. The specification requires a minimum hardness of Rc 59 to a depth of .020-.050". The measured case depths in the test gears and pinions however were in the range .018-.031". Furthermore, it was observed that the overall case hardnesses in the forged gear and pinion were consistently higher than in the cut parts. These differences are presumed to be a result of differences in the depth of final grinding. Likewise the overall shallowness of the case depths is attributed to an excessive amount of final grinding.

The hardness of both gears and pinions at the surface were found to be closely matched. The largest difference in surface hardness was found to be 3 hardness units on the Rockwell C scale among the 4 test pieces. This lends credibility to the fatigue tests since fatigue failures are known to initiate in the surface layer.

Photomicrographs of the hardened case in the cut and forged gear and pinion teeth are shown in Figures 54 and 55. These photos substantiate the case depth differences indicated by the microhardness results. In the gear photographs shown in Figure 54 some evidence of forging flow lines is apparent. The texture is perpendicular to the surface in the cut gear while the forged gear exhibits lines which are at a small angle to the surface. A more explicit flow line evaluation is presented in Section 7.2.2.

7.2.2 Metallurgical Structure

A primary technical objective of this gear forging program was to obtain a favorable forging flow line pattern in the gear teeth. It is generally acknowledged that fatigue endurance and tensile ductility are enhanced in the direction of forging flow, thus it was desirable to obtain a flow line pattern parallel to the tooth surface. The principal loading stresses are applied parallel to the surface when the gear is in normal service.

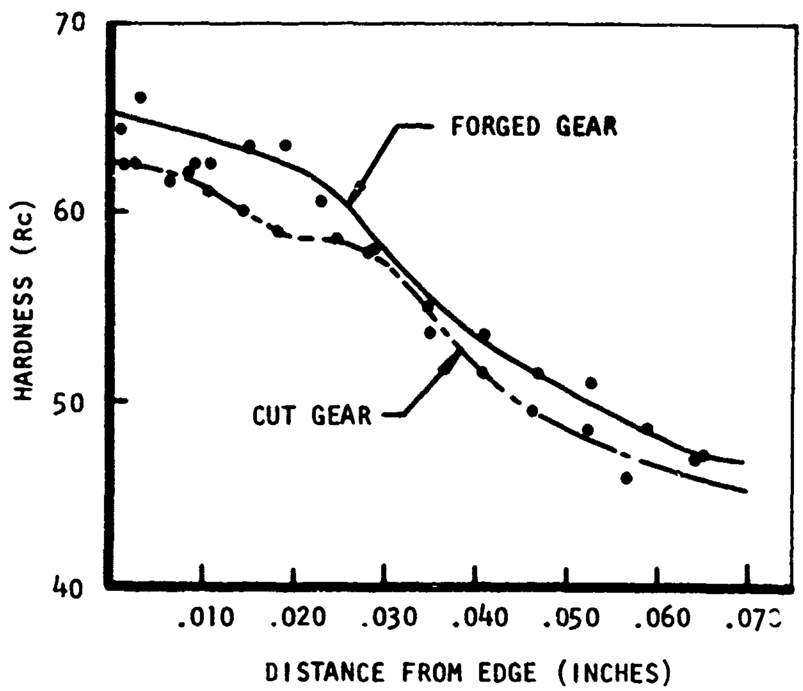


Figure 52. CASE HARDNESS PROFILES IN CUT AND FORGED GEAR TEETH

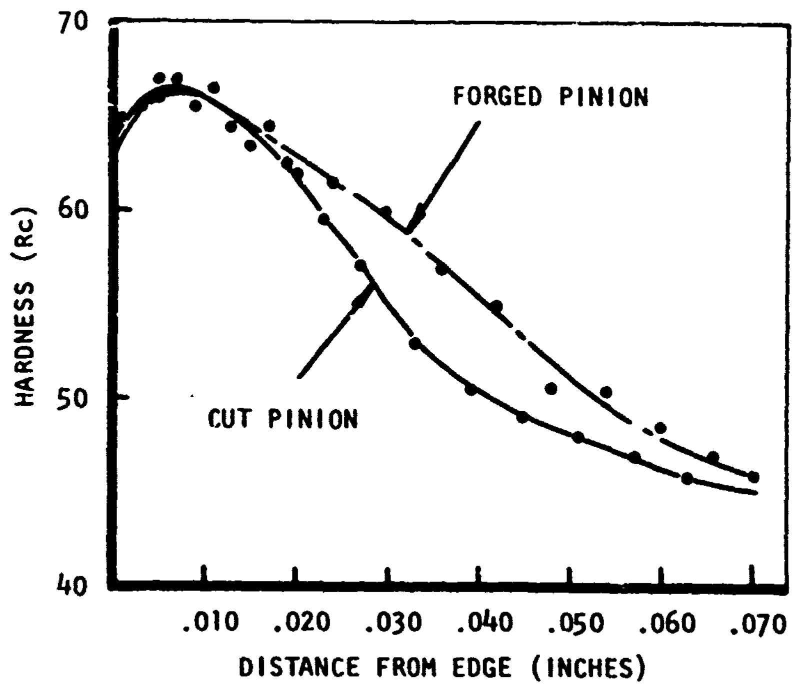
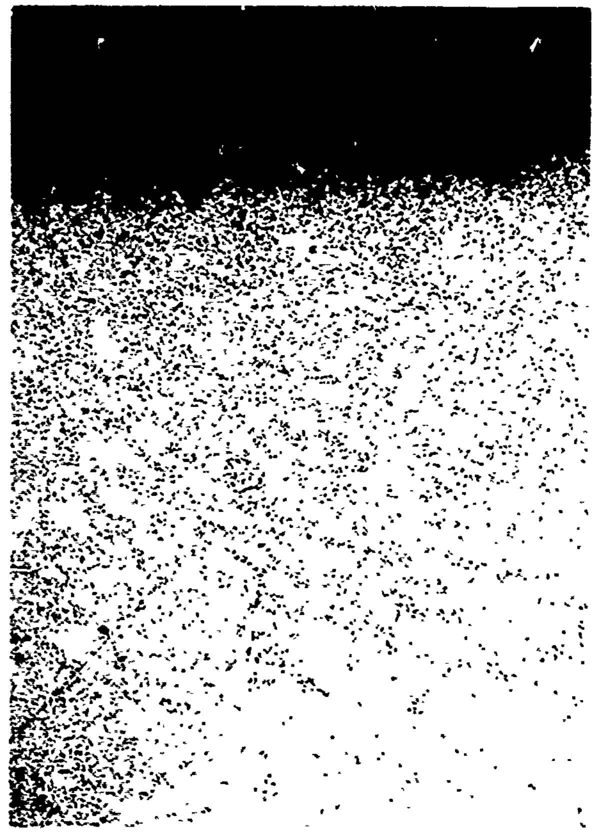


Figure 53. CASE HARDNESS PROFILES IN CUT AND FORGED PINION TEETH

Cut Gear

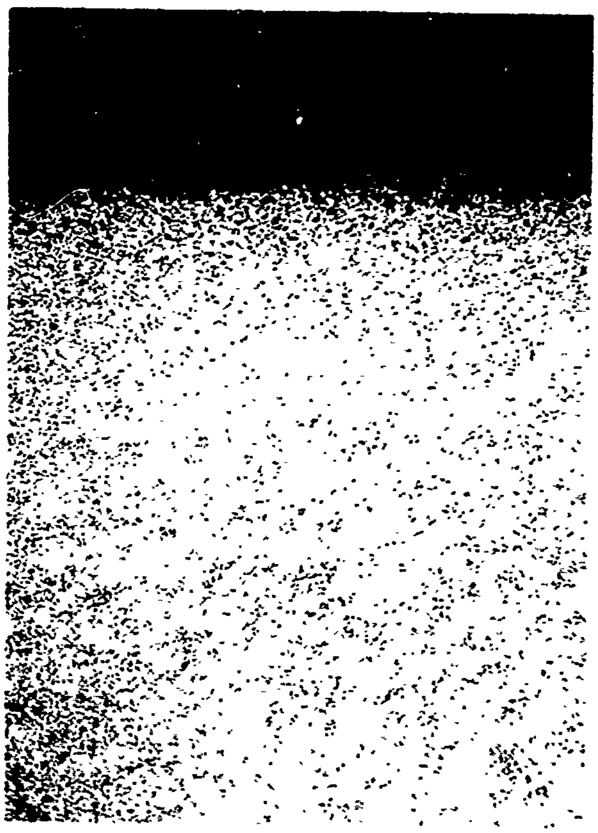
50X



Forged Gear

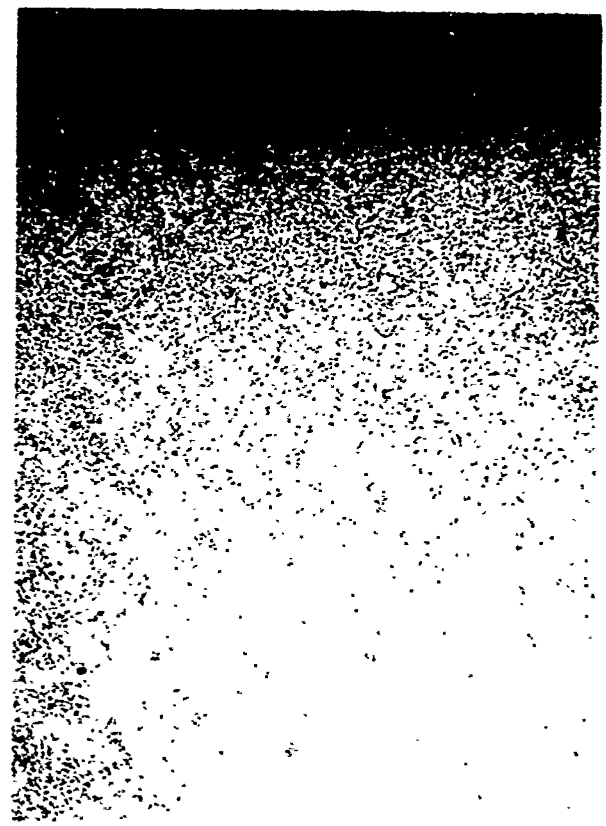
50X

Figure 54. Carburized surfaces of cut and forged test gears.
(50X, Nital etch)



Forged Pinion

50X



Cut Pinion

50X

Figure 55. Carburized surfaces of forged and cut test pinions)
(50X, Nital Etch)

The forging flow line pattern obtained along the length of a gear tooth in the forged test gears was determined by sectioning to obtain tooth profiles at three locations and then macroetching the profile sections with a concentrated hydrocholoric acid solution. The flow line pattern revealed by etching is shown in Figure 56 for the three locations within the gear tooth. These macrographs indicate that a favorable forging flow line pattern, consisting of lines parallel to the surface of the tooth, is present along the entire length of the tooth. This contrasts favorably with the pattern generally obtained in cut gears in which flow lines which originated in the blank forging operation, intersect the surface of the tooth at most locations.

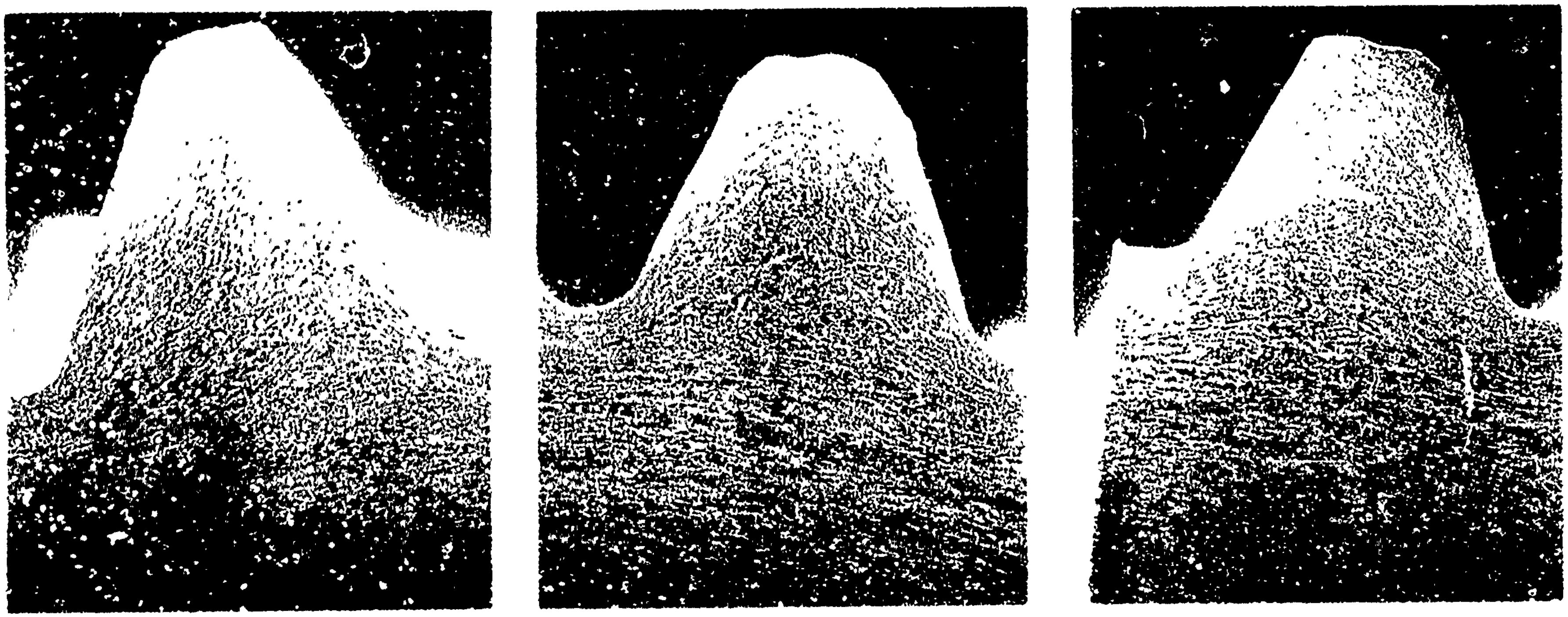
Another aspect of metallurgical structure which was evaluated was the macrostructure in the core (away from the hardened case) of the forged and cut teeth. This was done to detect any differences in structure which may have resulted from the forging versus cutting method of processing. A typical core microstructure for the two types of gear teeth are shown in Figure 57. Both structures consist of tempered martensite and no significant difference in the size or morphology of the constituents was found.

Finally, a cursory examination of gross carbides in the hardened case was made by a selective etching method in which the matrix structures were over etched to reveal the pattern of carbides which appear as small white particles against the dark matrix as shown in Figure 58. The size, amount and shape of the carbides was found to be essentially the same in the hardened case of cut and forged teeth after final heat treatment.

7.2.3 Tooth Failures

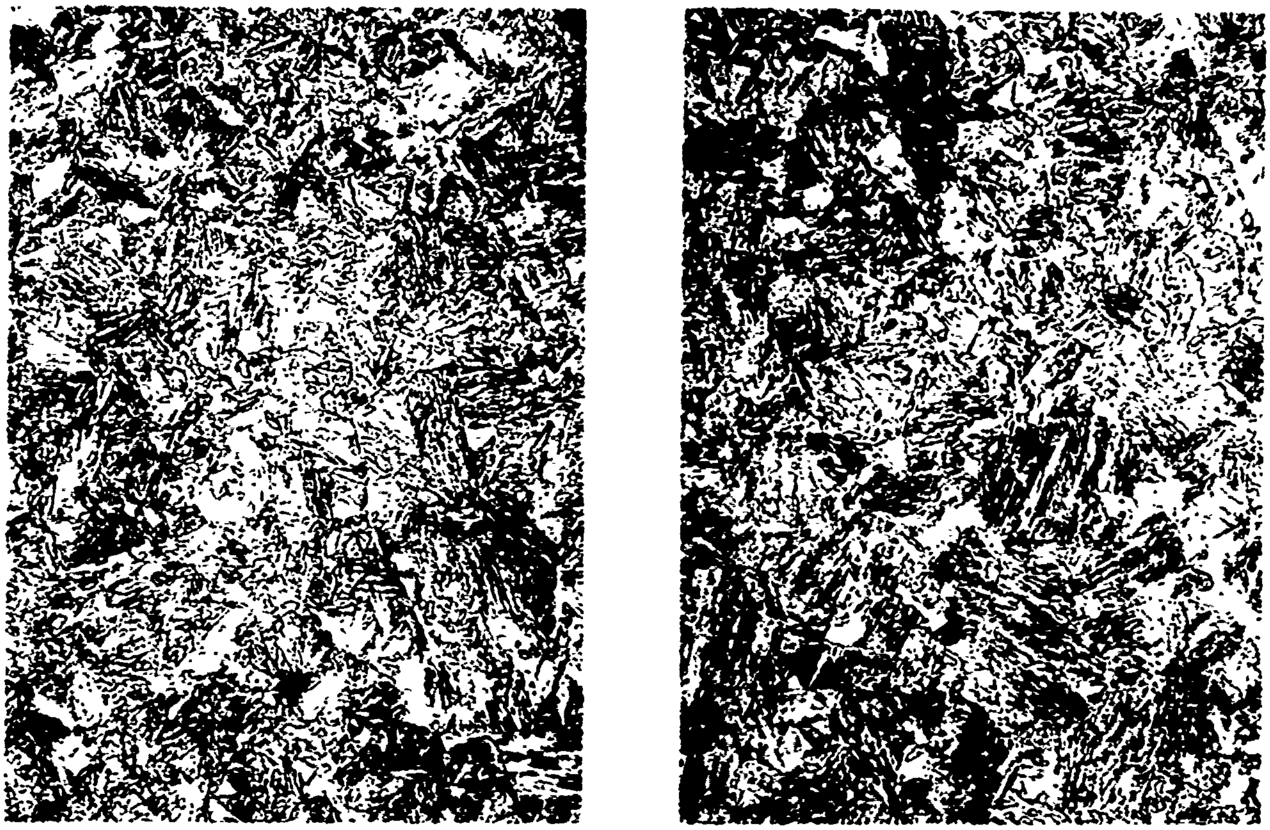
In the previous section it was shown that the mechanical fibering which results from forging flow is considerably different between cut and forged gears. This fibering consists of the preferential alignment of inclusions and second phase particles in the direction of forging flow. Because these constituents can act as notches to control the mode of fracture it can be expected that the fracture path in cut and forged gears might be affected.

The fatigue failures experienced during the single tooth bending tests described earlier showed a distinct difference in fracture path between cut and forged teeth. As shown in Figure 59 the failures in cut gears tend to follow a continuous path originating near the toe and near the tooth tip propagating toward the heel and toward the tooth root. The typical failure in the forged tooth, as shown in Figure 60, was discontinous. The initiation of fracture occurred at the same location as in the cut tooth and initially proceeded in a similar fashion, but then jogged toward the tooth tip to form a V-shaped fracture path. This difference in fracture path was a consistent one and is presumed to be associated with references in mechanical fibering between the two types of teeth.



Heel | Middle | Toe

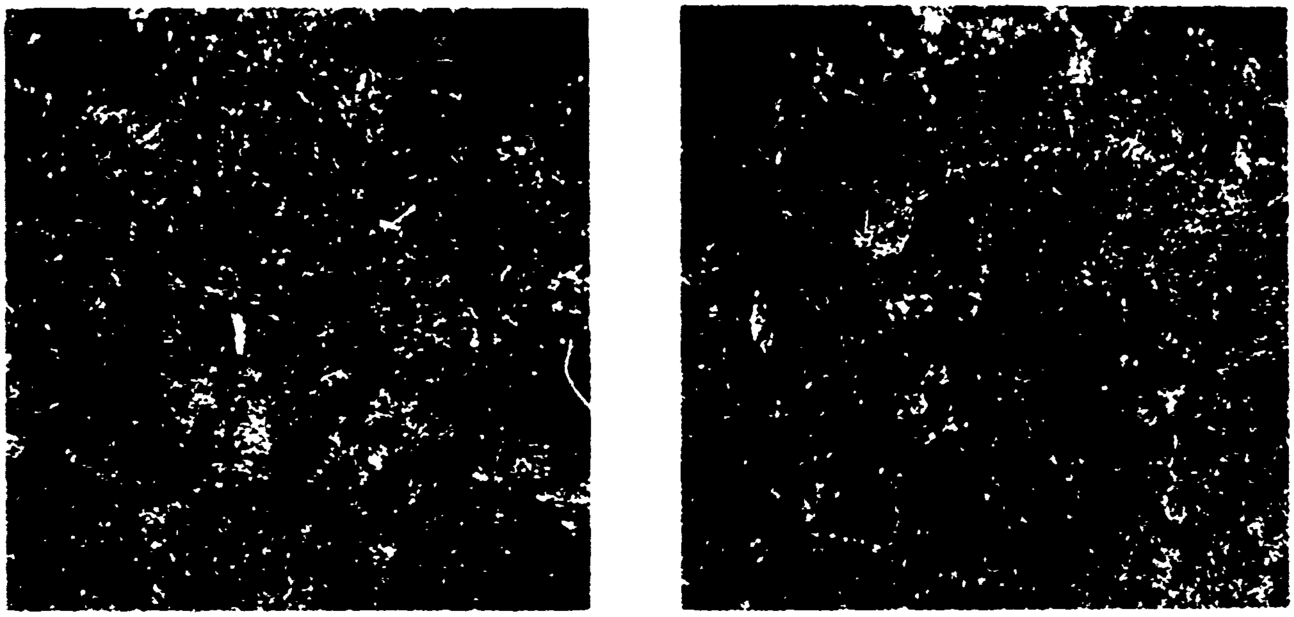
Figure 56. Tooth profiles showing forging flow lines at three locations along a forged gear tooth. (6X, HCl etch)



Cut Gear

Forged Gear

Figure 57. Microstructures in the core of cut and forged gear teeth after final heat treatment. (500X)



Cut Gear

Forged Gear

Figure 58. Comparison of carbide pattern in the hardened case of cut and forged teeth. (1000X)

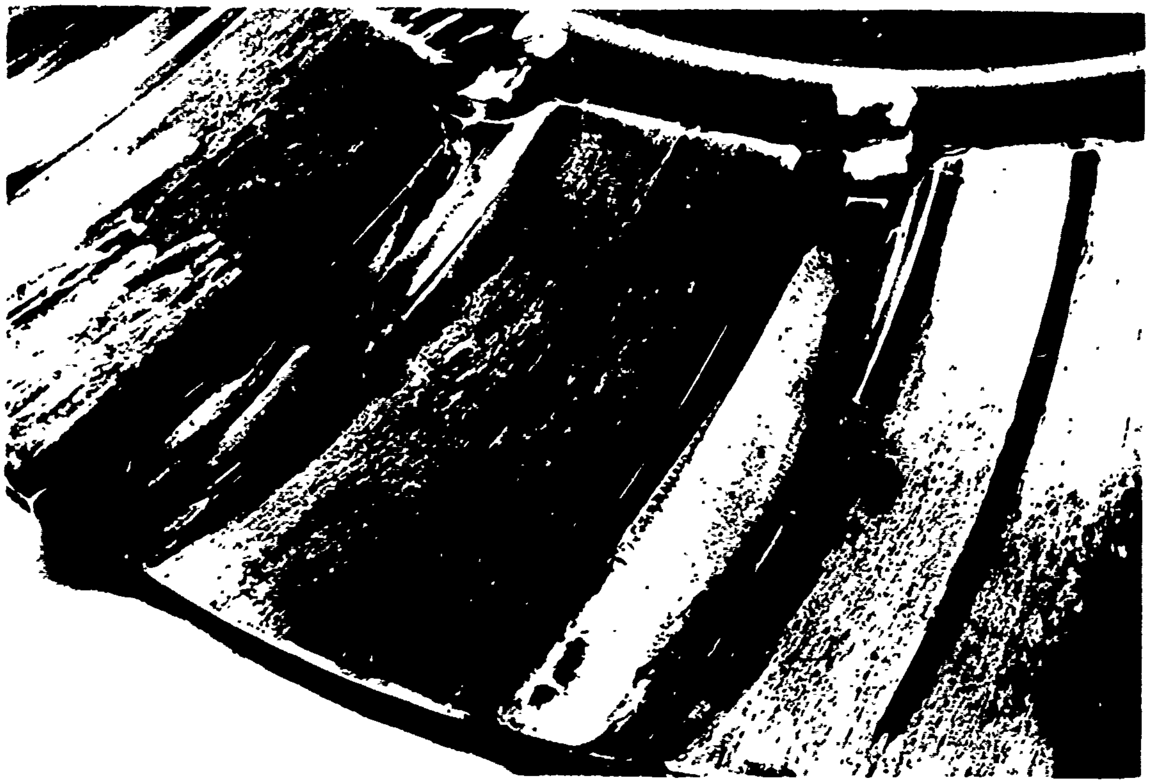


Figure 59. Typical fatigue failures in cut teeth showing continuous fracture paths.

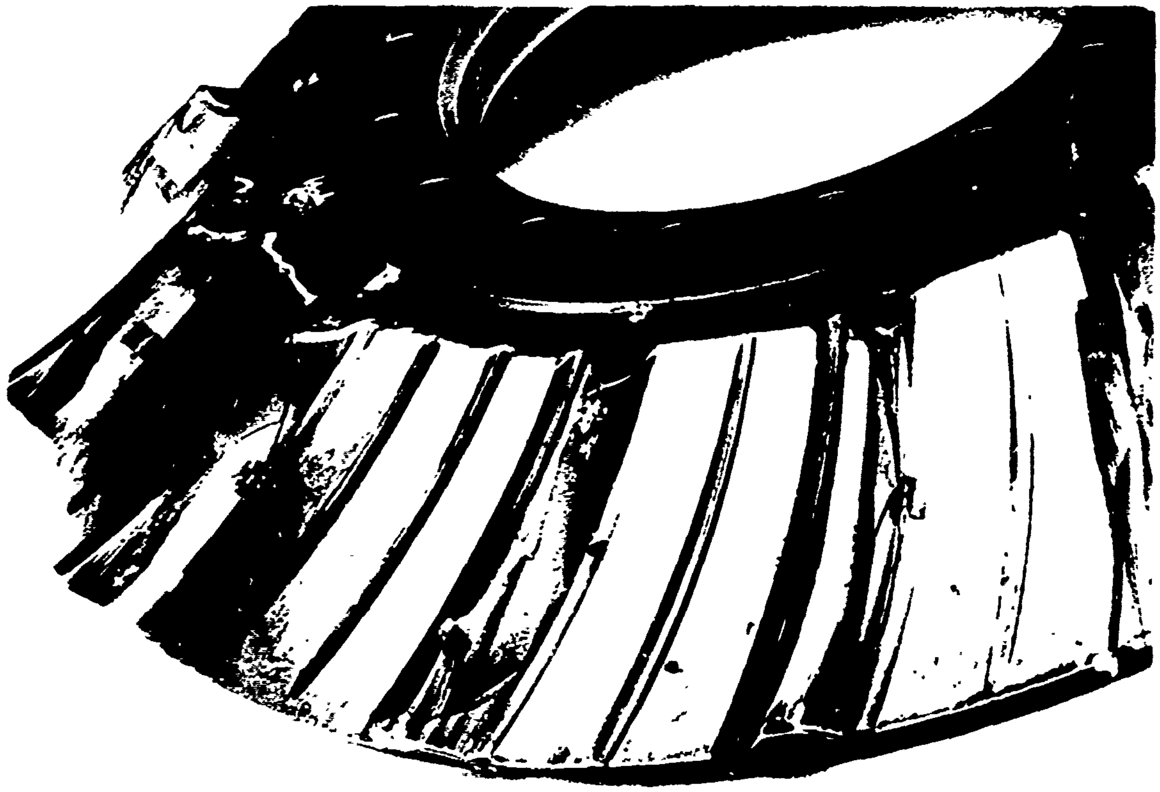
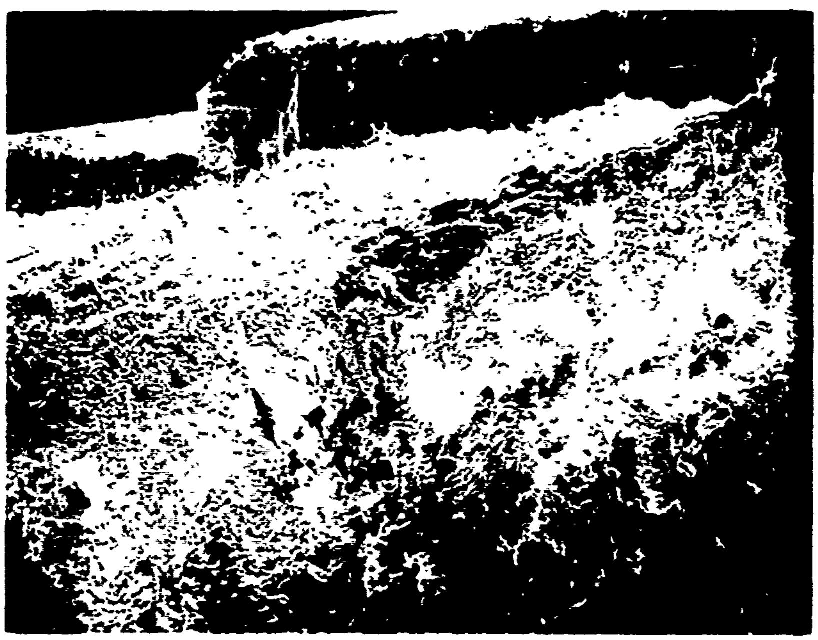


Figure 60. Typical fatigue failures in forged teeth showing discontinuous V-shaped fracture paths.

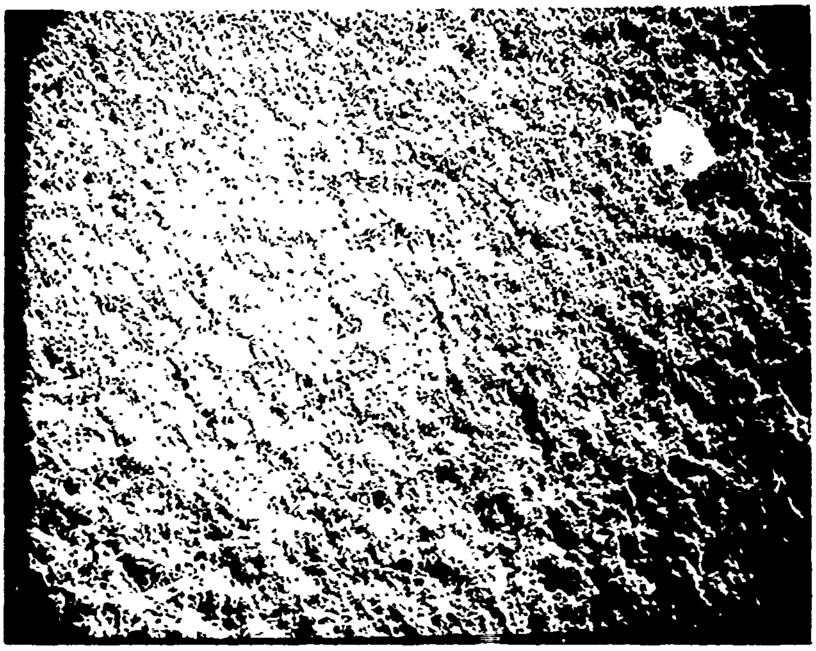
The failure evaluation was then extended to include a scanning electron microscope evaluation of the fracture surfaces of cut and forged gear teeth which had failed during the single tooth fatigue tests. Again, evidence of differences in the mode of failure was sought. Of particular importance was the mode of crack initiation because, for practical purposes, this initiation constitutes failure of the part. Therefore, SEM photographs of the fatigue crack initiation site in both cut and forged teeth were taken and these are presented in Figure 61. It was found that initiation occurred at the same location for a given load in both types of teeth, but consistent and distinct differences in fracture appearance were found. In the forged gear small cracks near the initiation point were found parallel to the surface while the direction of the cracks in the cut gear were normal to the surface. This difference is presumed to be associated with the difference in mechanical fibering direction in the teeth. As expected, the direction of the cracks is parallel to the fiber direction. The fracture surfaces away from the initiation point, as shown in Figure 62, did not exhibit a significant diffe ence in appearance.

Cut Gear

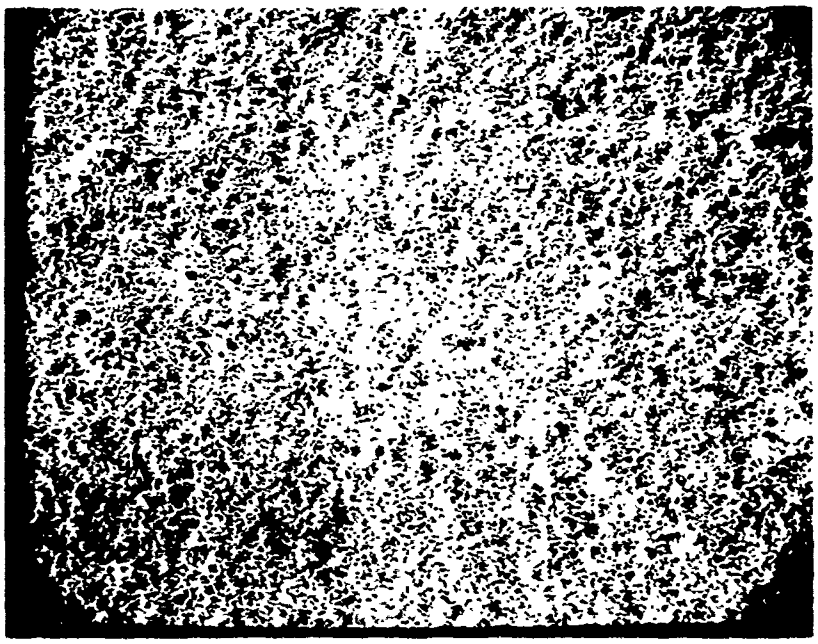


Forged Gear

Figure 61. SEM photographs of fracture surfaces at the site of failure initiation. 40X



Cut Gear



Forged Gear

Figure 62. SEM photographs of fracture surfaces away from the site of failure initiation. 40X

8.0 ECONOMIC ANALYSIS

The cost information compiled in the performance of this program is the basis for an analysis of the economics for the precision forging gear teeth and finishing the forging to the drawing requirements for production. Since the conclusions drawn from this analysis are extrapolations of available information, some of the assumptions and precepts are presented as follows:

1. The use of "Standard Hours" is employed as a basis for cost comparisons, instead of dollars, because it is a common denominator and eliminates the variables of overhead and other mark-ups that are peculiar to different organizations. In this study the "Standard Hours" were those actually observed and factored for practical efficiency, or were calculated from standard labor data generally in use throughout the metal working industry.

2. The forging lot size was established at 500 pieces, the same as the projected die life. The order size was set at 2500 pieces to fully utilize the die insert for four resinking cycles.

3. A machining lot size of 100 pieces, consistent with recent production practice, was selected.

4. Materials and purchased services are given in actual dollar costs to the program. Good purchasing practices were used but no attempt is made in this analysis to evaluate the cost effectiveness of purchased items.

5. The analysis is applied only to the operations that lead up to the carburizing-hardening operations. At this point the precision forged gear and the conventionally produced gear are finish processed in an identical manner. This analysis compares only the differences in the two processes in terms of direct labor and materials.

6. Quality control and inspection, important functions in both the forging process and the conventional process, are not considered direct costs in either instance. It has been assumed that this cost, per general practice, will be an indirect one and equivalent for each process.

8.1 Direct Labor Operations and Material Costs

The direct labor operations are shown in Tables XXV and XXVI for the precision forging approach and the conventional processing respectively.

Table XXV

Direct Labor for Precision Forging Process

AIRFOIL-COMPONENTS EST. NO. T.R.W. ______
PREVIOUS ESTIMATES ______
PART NAME SPIRAL BEVEL GEAR
PART NUMBER SK22270-FX729983-4
CUSTOMER AUSCOM, BOEING VERTOL
ENGINE CH-47 HELICOPTER
TPP-O-8907 PRINTED IN U.S.A.

MATERIAL AMS 6265
WT. PER 100 PCS 1600 LB
STOCK SIZE 3.50 DIA. CRD.
SHEET 1 OF 2
DATE ______ BY ______

OPER. NO.	OPERATION	GROUP TRW	MACHINE DESCRIPTION AND TOOLING REQUIRED	STD.HRS. PER PC.		HOURS	TOOLING ESTIMATE							
							COST FOR EACH							
				MAN	MACH	SET UP 500/lot	DESIGN	BUILD	NO.	TOTAL	NO.	TOTAL	NO.	TOTAL
10	RECEIVE ST'K - NOTE CERT.		$.65/LB	•									16#	10.40
20	INSPECT - AMS SPEC	8851		•										
30	CUT BILLET TO LENGTH	T.R.	DO ALL	.070	.14	1.0								
40	SQUARE ENDS & CHAMFER	T.R.	LATHE AUTOMATIC	.035		3.0								
50	HEAT FOR FORGING	623-11	J-28 ROTARY-EXOGAS FURNACE		.08	1.0								
60	PREFORM & FINISH HOT COIN	623-11	J-28 - 2000T MAXIPRESS	.10	.08	9.0								1.60
70	INSPECT - STAMP SER. NO.	623-91	SCHMIDT	.015	.015	1.0								
80	CLEAN	655-12	WHEEL ABRATOR - TABLAST	.015	.015	-								
90	MAGNAFLUX - 100%	623-91	MAG UNIT	• .055	.055	-								
100	INSPECT & RECORD - 10%	623-91	BENCH & GAGES	• .03	-	-								
		H-R				1.00/LOT								
130	TURN EXCESS STOCK - DRILL RE STAMP	619-32	ENGINE LATHE	.170		1.0								
140	LOC ON FIXT. GRD FACE & O.D.	881-42	HEALD INT. GRINDER	.200		1.5								
150	TURN & BORE	513-30	TURRET LATHE	.300		3.0								
160	FACE, TURN O.D.& C BORE	627-32	ENGINE LATHE	.200		1.5								
170	GRINDFACE & O.D.	881-42	HEALD INT. GRINDER	.175		1.5								
			SHEET TOTALS											

Table XXV (continued)

TRU SK-22270		SHEET 2 OF 2					TOOLING ESTIMATE							
OPER. NO.	OPERATION	GROUP	MACHINE DESCRIPTION AND TOOLING REQUIRED	STD. HRS. PER PC. MAN	MACH.	HOURS SET-UP	COST FOR EACH DESIGN	BUILD	NO.	TOTAL	NO.	TOTAL	NO.	TOTAL
180	GRIND BORE & FACE	886-42	BRYANT INT'L GRINDER	.150		2.5								
190	GRIND BORE & FACE	881-42	HEALD INT'L GRINDER	.100		1.0								
200	TRANSFER IDENTITY	989-46	BENCH	.020										
210	TRACE WEB CONTOUR	526-41	TRACER LATHE	.200		2.5								
220	SEMI-FIN TURN GROOVE	618-32	ENGINE LATHE	.120		1.5								
240	POLISH WEB	953-46	POLISHING MACHINE	.060										
250	VIBRO ETCH	989-46	BENCH	.020										
260	ROUGH TURN GEAR ANGLES	614-32	DOUBLE COMPOUND LATHE	.110		2.0								
270	FINISH TURN GEAR ANGLES	614-32	DOUBLE COMPOUND LATHE	.110		1.0								
280	POLISH	953-46	POLISH LATHE	.040										
290	WASH	996-46	WASH MACHINE *											
300	INSPECT & RECORD	900-68	BENCH *	.070										
			*INDIRECT COST											
			SHEET TOTAL(S)	.930		10.5								
			GRAND TOTAL	2.190		22.0								

TYPO-... FO. 2 PRINTED IN U.S.A.

Table XXVI

Direct Labor for Conventional Process

AIRFOIL-COMPONENTS EST. NO. T.R.W. ______
PREVIOUS ESTIMATES ______
PART NAME SPIRAL BEVEL GEAR
PART NUMBER 114D6245-1
CUSTOMER BOEING - VERTOL
ENGINE CH-47 HELICOPTER
TPFC-3007 PRINTED IN U.S.A.

MATERIAL AMS-6265
WT PER 100 PCS. ______
STOCK SIZE FORGING - BM57-C
SHEET 1 OF 1
DATE ______ BY ______

OPER. NO.	OPERATION	GROUP H-R	MACHINE DESCRIPTION AND TOOLING REQUIRED	STD.HRS. PER PC. MAN	STD.HRS. PER PC. M/CH.	HOURS SET-UP	TOOLING ESTIMATE: COST FOR EACH DESIGN	COST FOR EACH BUILD	NO	TOTAL	NO.	TOTAL	NO.	TOTAL
5	PROCURE FORGING BLANK													29.98
10	INSPECT FORGING	890-68												
20	STAMP	989-46	BENCH	.024										
30	FACE & BORE	511-30	W&S TURRET LATHE	.220		2.0								
40	TURN O.D.	511-30	W&S TURRET LATHE	.090		2.0								
50	TRACE WEB & BORE I.D.	526-41	W&S TURRET LATHE	.220		2.0								
60	TURN MTG FCE	613-32	ENGINE LATHE	.125		2.0								
70	GRIND BORE & (2) FACES	886-42	BRYANT INTERNAL GRINDER	.333		2.5								
80	SEMI-FINISH TURN GROOVE	618-32	ENGINE LATHE	.120		1.5								
90	STAMP	989-46	BENCH	.020										
95	POLISH	953-46		.060										
100	ROUGH TURN GEAR ANGLES	614-32	DOUBLE COMPOUND LATHE	.110		2.0								
110	FINISH TURN GEAR ANGLES	614-32	DOUBLE COMPOUND LATHE	.110		1.0								
120	POLISH	953-46	POLISHING LATHE	.040										
130	WASH & INSPECT & RECORD	900-68	BENCH											
140	GENERATE GEAR TEETH	819-37	GLEASON GEAR CUTTER	.400		5.0								
			SHEET TOTALS	2.072		20.0								

The tables describe the operations by title and show the labor hours per unit and the set-up time for the lot. The comparable direct labor, including set-up labor, is 1.514 hours for precision forging and 2.072 hours for conventional processing.

Material costs for the two processes are shown in dollars. The material cost of $10.40 for the precision forging process is for ground bar stock. For the conventional process the material cost is $29.88 for the normal oversize forging blank.

8.2 Direct Costs of Consumable Tooling for Precision Forging

This category of perishable tooling costs was the most obscure and uncertain cost factor before this program of development was specifically directed to organize and compile the pertinent facts. The hot coining die, designed to properly form the gear teeth, is considered the major consumable tool directly affecting the cost of the process. The dimensions on the forged teeth are of course established by the configuration in the die cavity. The cavity, in turn, is developed from the forms of the EDM electrodes used to sink the cavity in the die. These electrodes are consumed or eroded during the process and for this study will be considered a direct cost item.

It has been established that each electrode, as presently designed, can be recut three to four times. However, a set-up charge is involved for each recut. The set-up charge of $375.00 is approximately equal to the cost of three blanks, so for this analysis the cost of the full suppiy of new electrodes is determined and prorated over the total die life consisting of four resinks after the original cavitation. The utilization of electrodes is shown in Table XXVII.

The seven roughing and seven finishing electrodes will be less than 25% utilized in the cycle shown in the table. The residual value for continued production or conversion to another gear design is not considered in the final analysis.

The electrodes withdrawn from this cycle, i.e., 2R and 1F could be recut and reintroduced into the sequence as 4R and 4F. Subsequently withdrawn electrodes could be similarly recycled to reduce the initial quantity to three each of the roughing and finishing electrodes. However, the $1,200 saved in the cost of the blanks is outweighed by the six set-up charges of $375.00 each or $2,250.00

The dollar cost for electrodes is shown in Table XXVIII. The table also shows the direct labor cost for resinking the die. The resinking operation has been considered a service normally performed in support of the forging operation and is shown in standard hours. The EDM standard hours are for one operator to four machines. EDM machines are usually operated in batteries with one operator running more than one machine when cutting cycle times permit.

Table XXVII

EDM Electrode Utilization

Electrode Number Into Operation	Die and Electrode Sequence Used	Electrode Number Withdrawn for Recutting
	Original Cavity	
1R, 2R, 3R	1R, 2R, 3R	1R, 2R, 1F
1F, 2F, 3F	1F, 2F, 3F	
	1st Resink	
4R	3R, 4R	3R, 2F
4F	2F, 3F, 4F	
	2nd Resink	
5R	4R, 5R	4R
5F	3F, 4F, 5F	3F
	3rd Resink	
6R	5R, 6R	5R
6F	4F, 5F, 6F	4F
	4th Resink	
7R	6R, 7R	6R
7F	5F, 6F, 7F	5F

Table XXVIII

Direct and Consumable Tooling Cost for Precision Forging

AIRFOIL COMPONENTS EST. NO. T.R.W. ______
PREVIOUS ESTIMATES ______
PART NAME ______
PART NUMBER ______
CUSTOMER ______
ENGINE ______

DIRECT & CONSUMABLE TOOLING COST FOR PRECISION FORGING

MATERIAL ______
WT PER 100 PCS. ______
STOCK SIZE ______
SHEET ____ OF ____
DATE ____ BY ____

OPER. NO.	OPERATION	GROUP	MACHINE DESCRIPTION AND TOOLING REQUIRED	STD. HRS. EA. PC.		HOURS SET-UP	TOOLING ESTIMATE							
							COST FOR EACH				HRS. 2500 PC LOT		2500 PC LOT	
				MAN	MACH.		DESIGN	BUILT	NO	TOTAL	NO.	TOTAL	NO.	TOTAL
	DESIGN DIE SET		BF 13774				1500							
	FABRICATE DIE SET		BF 13774 MINUS DET 42					5000						
	FABRICATE - DIE INSERT		DET. 42 OF BF 13774											
	H-21 BILLET		17" DIA. X 3-3/4" - MATERIAL					510	1					510.00
	MACH. BLANK - H.T.							540	1					540.00
	BLANK EDM ELECTRODES		BE 14759											
	ROUGHING		DET. 2					150	7					1050.00
	FINISHING		DET. 1					125	7					875.00
	CUT EDM ELECTRODE		SET-UP CHARGE					375	1					375.00
	ROUGHING ELECTRODES		DET. 2					45	7					315.00
	FINISHING ELECT.		DET. 1					45	7					315.00
	SINK DIE CAVITY		BF 13774 - DET. 42	8.0	32.0	3.0			1			10.0		
	RESINK DIE CAVITY			6.5	24.0	2.0			4			34.0		
	INSPECTIONS -													
	NDT DIE BILLET			2.0					1					
	INSPECT ELECTRODES			1.0					7					
	INSPECT CAST OF DIE			2.0					5					
			SHEET TOTALS									44.0		3980.00

8.3 Cost Summary

The cost for the design and fabrication of the die set BF 13774 has been shown in Table XXVIII. This tooling provides for the hot finish coining for both the pinion and the gear and also for the forming of the bar stock into the forging preform. The cost of this major item is not applicable to the present analysis because only a very small fraction of the cost could be assigned to the quantity of gears under consideration. In addition, the costs for comparable fixtures and special tooling required for conventional processing, such as Gleason arbors and cutters, cannot be readily identified. Therefore, for the purpose of comparing relative costs for the two processes, the cost of permanent type fixtures and tools will be excluded.

The comparative costs for the two processes are given in Table XXIX.

Item 1 - shows the cost of the blank forging, including set-up and material, used for the conventional process. The comparable cost for the forged tooth process is the cost of the material in bar form.

Item 2 - is the direct labor hours for cutting the bar stock, making and cleaning the precision forging.

Item 3 - is the direct labor required for setting up for Item 2 operations.

Item 4 - shows the machining labor hours required to machine the forgings to a common configuration prior to the heat treat sequence. Some deburring operations that are common to both processes are not included in this total in order to simplify the summary.

Item 5 - is the labor hours required to set-up for each of the two processes. These hours have been prorated over 100 pieces.

Item 6 - is the prorated forging die cost. The blank insert cost, its preparation and the cost of EDM electrodes is shown as material and other direct charges (ODC). The labor hours to set-up and EDM the die cavity is shown as a direct labor cost.

Table XXIX

Comparative Cost Summary

Item	Conventional Process Standard Hours Piece	Conventional Process $ Cost/Piece	Precision Forging Process Standard Hours Piece	Precision Forging Process $ Cost/Piece
1. Material		29.88		10.40
2. Forging			.235	
3. Set-up			.030	
4. Machining Labor	2.072		1.045	
5. Set-up	.20		.190	
6. Die Cost -				
Labor -			.014	
Mat. ODC -				1.60
Total	2.272	29.88	1.514	12.00

The results given in the above table show that the forging of gear teeth results in an economic advantage over a conventionally manufactured gear.

The scope of the program did not provide for the forging of a quantity of pinions representative of a production run. However, it is possible to estimate a saving of approximately thirty dollars in material and .3 standard direct hours for each forged tooth pinion.

9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 Economic

1. The precision forging of gears is a feasible cost reduction approach in the production of certain spiral bevel gear designs.

2. The dimensional and surface quality of the forgings are reproducible and the yield for the precision forged gear should be good.

3. The lead time to process quantities of gears through the operations up to heat treatment is reduced due to the elimination of the Gleason gear cutting operation which tends to bottleneck the flow of parts.

4. An allowance must be made for some development for each new gear design.

9.2 Technical

1. The mechanical properties of forged teeth have a high fatigue limit as compared to cut teeth. Additional testing, especially rolling contact testing, is required. A full scale qualification test program for the design used in this development (or another production design) is recommended.

2. The metrology requires some refinement for more economical production. The approaches developed on this program were proven sound in concept.

3. The surface quality of the forged teeth was adequately preserved by nickel plating the billet. Other methods of eliminating scaling should be developed to further improve the surface and reduce costs.

4. It is recommended that the finish lapping of forged tooth gear sets be investigated. The value of the precision finish grinding the gear teeth for interchangeability is not realized if gears are replaced as sets.

9.3 Production Potential

1. The processes developed and presented on this program are practical and readily applicable to production. However, adoption by industry, especially the aircraft industry, will be limited by considerations other than performance and economics. Qualifying the process to FAA, and other standard regulations, such as AGMA, is required before production will result.

2. It is recommended that the Army coordinate the selection, production and overall evaluation of a specific spiral gear set with a substantial production potential.

3. The forging forces required on the crank press are relatively low to achieve good definition. Existing presses could form gears up to 30" diameters if the die sinking electrode and EDM equipment were available. A study to establish the feasibility of scale-up is recommended.

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APPENDIX A

DEVELOPMENT OF METROLOGY TECHNIQUE FOR SPIRAL BEVEL GEARS

The dimensional control of the forged gear teeth is a key prerequisite to the successful and practical utilization of the forging technique. However, the control of the forging dimensions is indirect. The female forging die cavity must be made from a generally conforming male EDM electrode. The modified tooth form of the electrode in turn is produced on a gear cutting machine. Allowances determined by analysis, must be made for tolerances, distortions, EDM over cutting, and thermal expansions and contractions. The ultimate refinements for forged spiral bevel gears must be done empirically at the final stage of development. The finished spiral bevel gears themselves are not completely described by dimensioned drawing, but are developed empirically using a proprietary Gleason gear system. With these difficulties in mind, the usefulness of directly measuring gear tooth characteristics on the EDM electrode, the die, the forging and the master gear is evident.

The principles of this spiral bevel gear measuring system, which will be described, are based on measuring and analyzing differences, in certain important dimensions rather than an attempt to relate finite values to the gear design requirements. A schematic of a forging is shown in Figure 1-A with the pertinent dimensions indicated by A, B, C, etc.

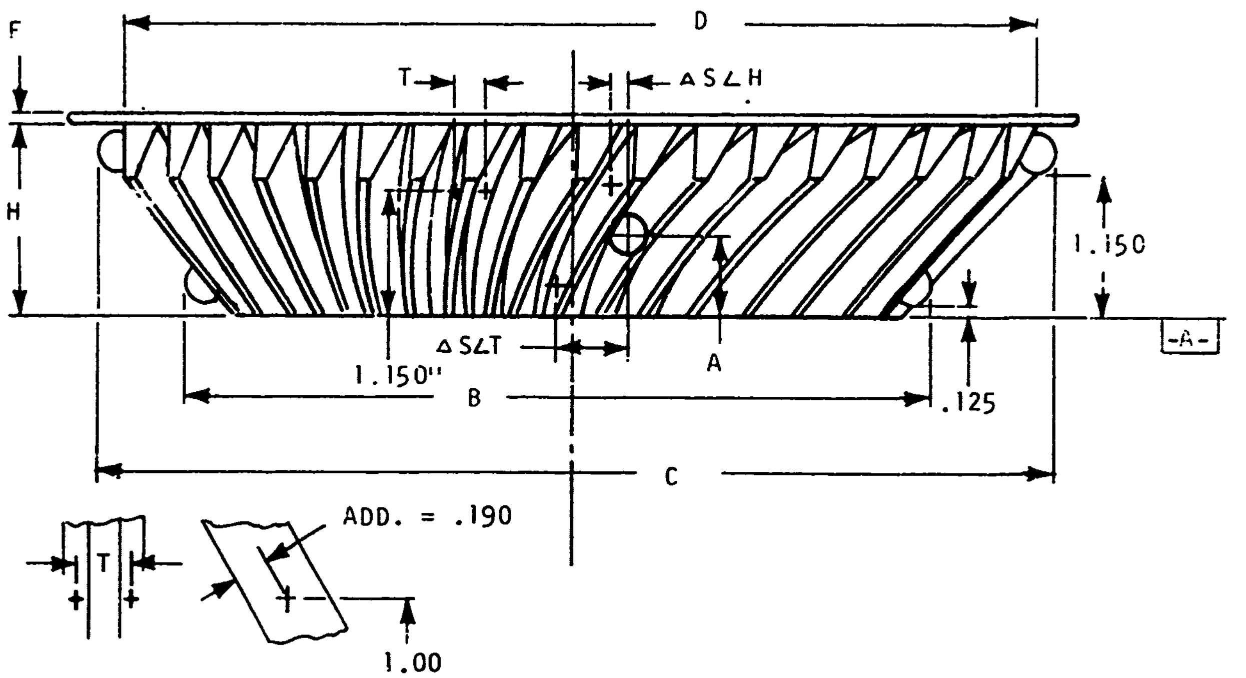
Major and Minor Dimensions

The major reference dimensions are:

1. "D" - gear O.D. is the concentricity reference.
2. "A" - a height dimension measured from a pitch circle plane, established by three locators on the pitch cone and at the center of the tooth face to the small end face of the electrode.

The minor reference dimensions are:

1. "B" - the pitch diameter measured over .2500" diameter balls tangent to a plane .125" inside of the plane of the end face.
2. "C" - the pitch diameter measured over .2812" diameter balls tangent to a plane 1.150" inside of the plane of the end face "A".
3. "F" - flash thickness.
4. "H" - overall depth of the form.
5. "ΔS∠H" - is the change in spiral angle at the heel. This is taken on the convex side of a tooth engaged by a locator and compared to a master gear. It is taken in a convenient but constant plane.



DIMENSIONS - .000

ITEM	A	.2500" BALL DIA. B	.2812" BALL DIA. C	D	F	H	ΔS∠T	ΔS∠T	T
MOLDING					-				
ELECTRODE	0				-	-			
FORGING									
CUT MASTER GR				-	-	-	0	0	

Figure 1a. Data sheet for gear data recording.

6. "ΔS∠T" - is the change in spiral angle at the toe, measured as in 5 above.

7. "T" - is the tooth thickness taken in one plane arbitrarily selected at 1.150" inside the plane of the end face "A".

These dimensions are arranged in the table in Figure 1A so that comparisons can be made between the master gear and the forging, electrode, or a molding of the die cavity.

Equipment and Procedures

The procedure developed to measure the forged gears, electrodes, master gear and cast of the die cavity is described in this section.

The "A" dimension is recorded as the relative axial position of the "A" datum surface in relation to a plane established by three locators on the pot fixture T-104978-1 or -2. The "A" datum surface for the forging, electrode and cast of the die cavity is the end face on the apex side. The datum for the master cut gear is the back thrust face on the bearing journal.

The item being checked is cleaned thoroughly and carefully placed in the appropriate pot fixture leveled and with the locators snugly engaged in the tooth spaces. The fixture base is placed on a large, true surface plate.

The finish gear electrode or the cut master gear can be set up for reference. A small dial gage (.030" range) is mounted on a stand and adjusted to zero on the end face as shown in Figure 2A. The electrode and the cast, similarly mounted, are recorded as differences in relation to the reference.

The master cut gear "A" dimension is recorded as the actual distance from the surface to the mounting flange face of the gear (apex side) or the thrust face on the pinion.

The B&C dimensions are gear diameters measured over balls engaged in the tooth spaces at fixed locations.

The reference gear forging is set on parallel blocks as shown in Figure 3A. The ball sizes are selected to engage the teeth near the pitch diameters at the locations shown. B and C are measured over the opposite balls in the teeth, noting that the odd number of teeth allows only an approximate measurement of the true diameter. The B&C diameters must be established at axial locations that are within the finish tooth face length for all the items measured.

The electrode and the cast are set on the parallel blocks and measured in a similar manner except that shims must be placed between the end faces and the blocks to maintain the axial location of the reference estabiished

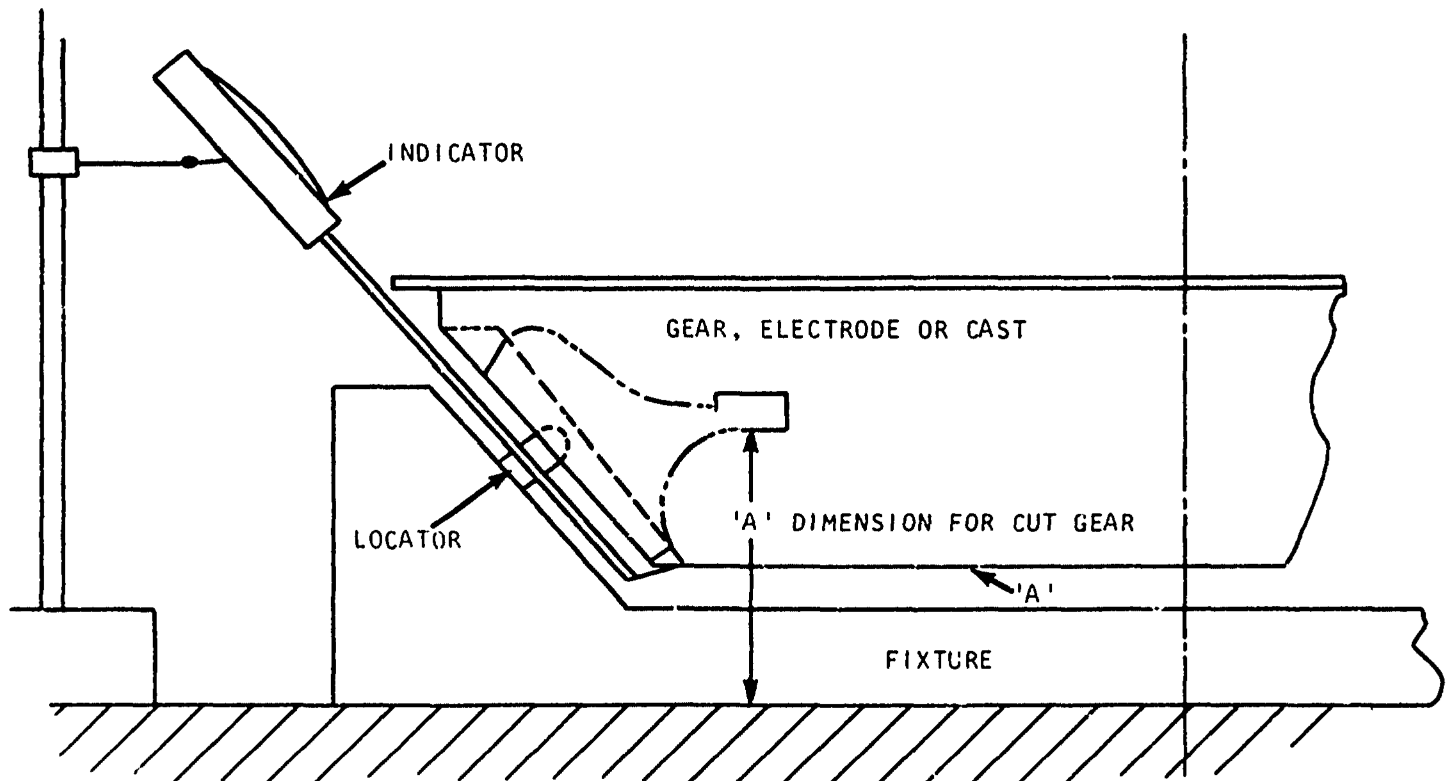


Figure 2a. Schematic of set-up to measure "ΔA".

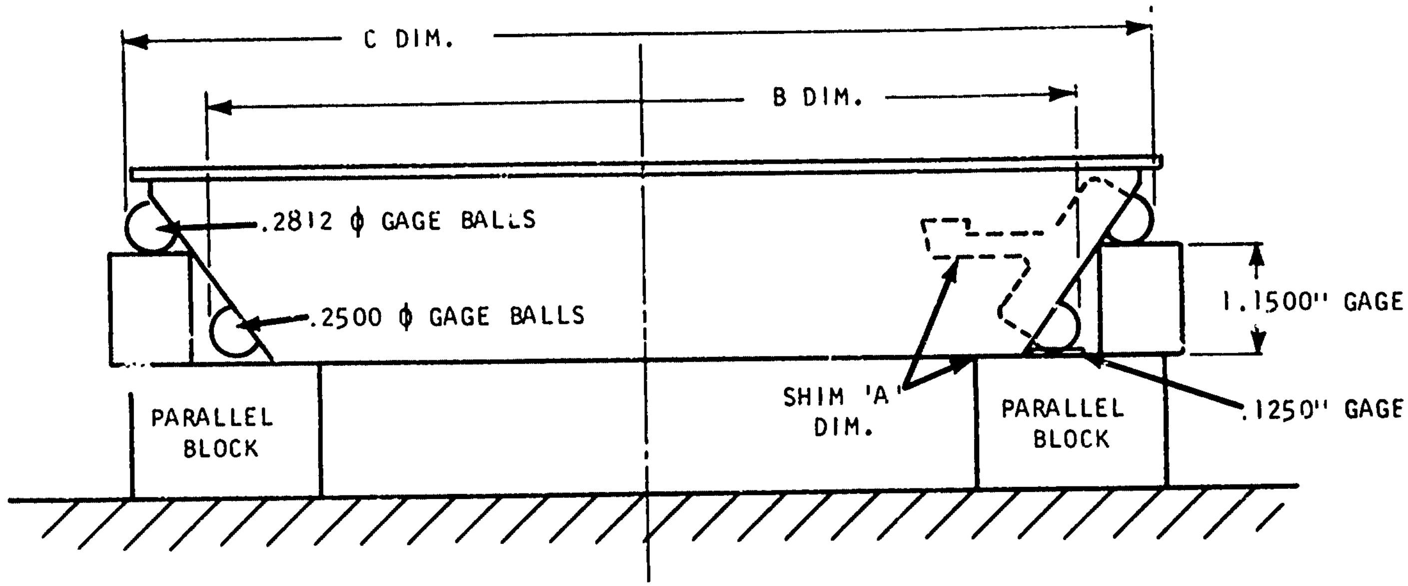


Figure 3a. Schematic of set-up to measure "B" and "C" diameters.

by the pot fixture locators. The shim thickness will be equal to the "A" reading to the nearest mil. The master cut gear or pinion is also set to the "A" height reading as measured previously.

A line is scribed on both sides of one tooth 1.150" above the parallel to the upper surface of the bar to establish the location for the tooth thickness measurement.

The D dimension is the outside diameter of the gear form and beyond the crown point. This dimension is measured directly on the forged gear, cast and electrode.

The dimensions for the ΔS∠H and ΔS∠T are relative readings in mils that indicate the change in tooth spiral angle at the heel (ΔS∠H) or change in tooth spiral angle at the toe (ΔS∠T). The measurements are recorded as variations from the master cut gear. The pot fixture T-104781-1 or -2 is used as a locator and is modified to allow access to the flank of one tooth at the toe. The spiral angle on the drive side of the teeth only is checked i.e., convex side of the gear tooth and the concave side of the pinion tooth.

The master cut gear is placed in the fixture and on the locators. The fixture is placed on a surface plate. Indicators are set to zero near the pitch line in about the planes of A and B. Without disturbing the fixture of indicator bases, the electrode, the cast, and the forged gear are set in the fixture and the variations in indicator readings are recorded. See Figure 4A.

The dimension "T" is the tooth thickness measured in the plane scribed in the B&C set up. The measurement is made at an addendum depth of .213" measured from the tip of the tooth and normal to the cone angle. See Figure 5A.

If .030" finishing stock is left on the tips of the forged teeth and the normal .007" is on the cut gear, the measurement will be taken on the cut tooth at a .190" addendum.

The F and H dimensions are the flash thickness and the gear forging cavity height respectively. They can be measured directly on the forging. The cavity height is measured and recorded for the cast.

The whole tooth depth on the gear can be measured directly on the electrode, forging and cast with the gage SK 103071JM shown in Figure 6A, bottom center. The gage is designed to locate on the "A" end surface and the top cone angle. This gage was intended to be used as an "in process" inspection tool to directly measure the effect of die wear on whole tooth depth. The whole tooth depth dimension was estimated to be the limiting factor in die life since it establishes the amount of stock to be removed in the critical forged root area.

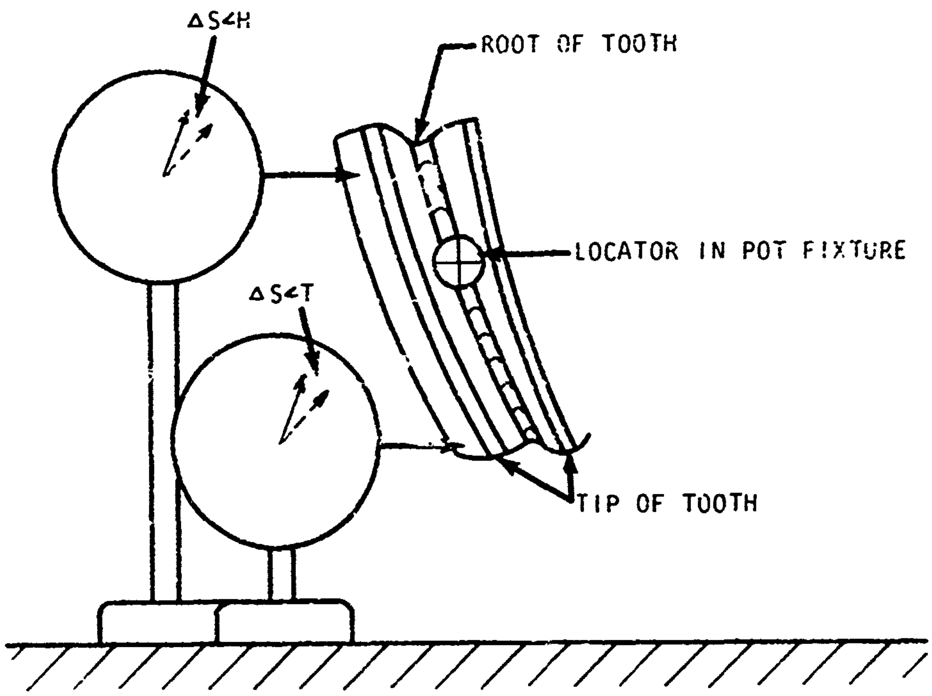


Figure 4a. Schematic of set-up to check spiral angle.

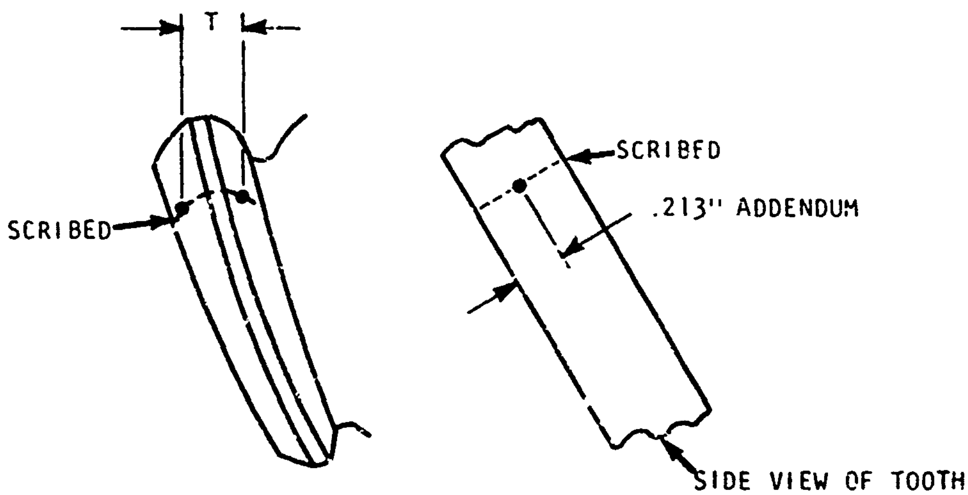


Figure 5a. Schematic showing location of tooth thickness measurement.

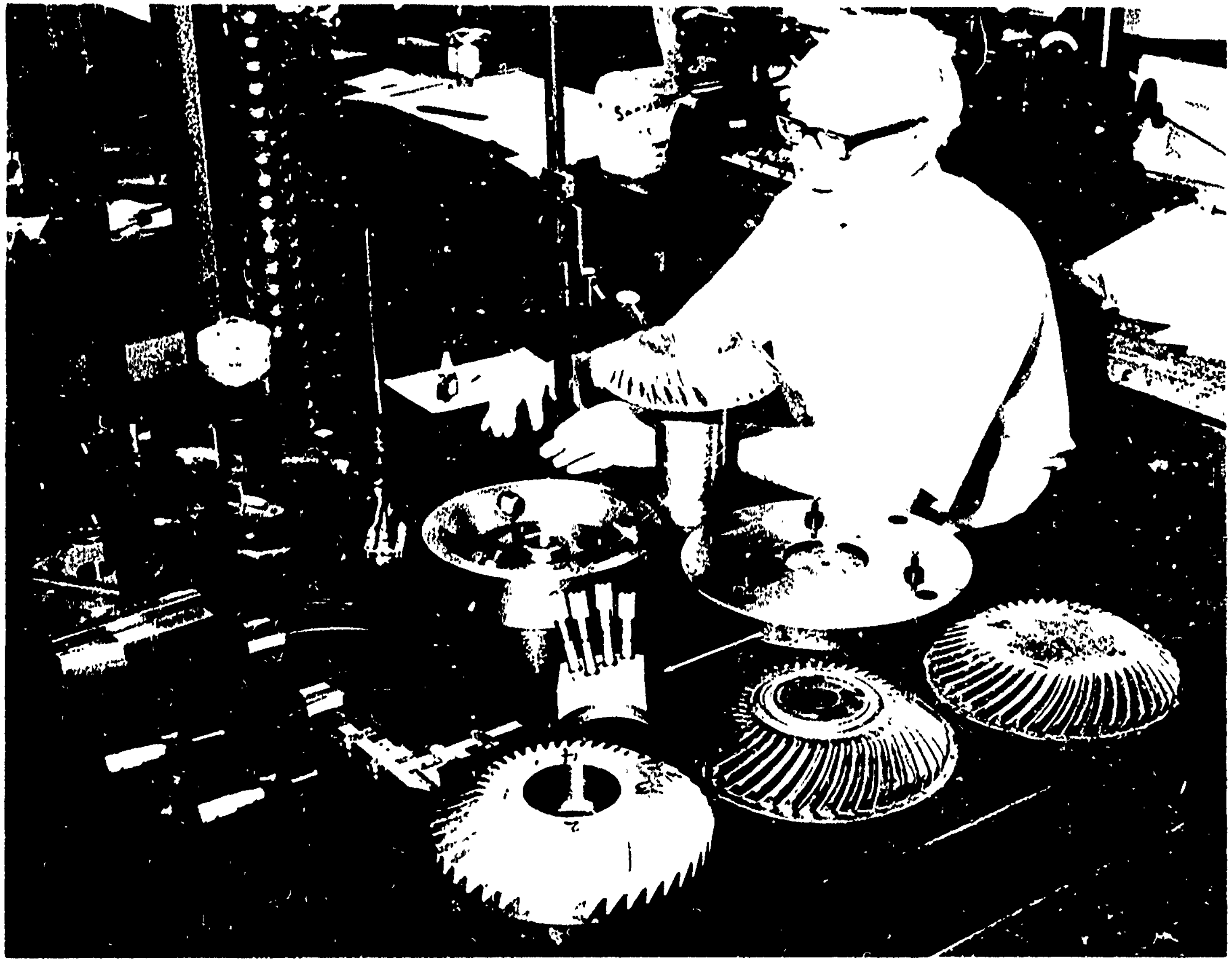


Figure 6a. Checking equipment required for gear development.

The equipment required to complete the procedure described in the previous section is illustrated in Figure 6A. Most of the items are standard tool inspection measuring instruments. The special fixture for locating the gear pitch plane is shown in the center of the figure. The special tooth depth gage was designed and built to directly check the effect of die wear on the forgings in the production run. The tool numbers for the special equipment are:

T-104978-1 - Locator for gear pitch plane

T-104978-2 - Locator for pinion pitch plane

SK-103071JM - Tooth depth gage

A functional production gage, capable of measuring all the desired characteristics, was designed. The gage was not built because the cost did not warrant it for the limited number of gears required for this program. The conceptual layout is applicable to future production if the volume is sufficient.